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Biot-Based Geoacoustic Investigation of Lake Arkabutla, Mississippi

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Contents

List of Tables

Preface

The work described in this report was performed during the period March to July 1999 by Mr. Richard G. McGee, senior coastal engineer, Evans-Hamilton, Inc., Seattle, WA. The work was performed under Contract No. DACW39-92-D-0012 and funded by the Earthquake Engineering (EQEN) Research Program project, "Geophysical Methods for Site Characterization and Measurement of Seismic Properties," Work Unit No. 33014.

This report was prepared by Mr. McGee and his staff at Evans-Hamilton, Principal Investigators for the EQEN Research Project, and Messrs. Robert F. Ballard, Jr., and Rodney L. Leist, members of the staff of U.S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, Earthquake Engineering and Geosciences Division (EEGD), Geotechnical Laboratory (GL). This work was performed under the general supervision of Dr. Lillian D. Wakeley, Acting Chief, EEGD, and Dr. Michael J. O'Connor, Director, GL. Dr. Mary Ellen Hynes was EQEN Project Manager.

At the time of publication of this report, Director of ERDC was Dr. James R. Houston, and Commander was COL James S. Weller, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic yards	0.7645	cubic meters
feet	0.3048	meters

1 Introduction

The Earthquake Engineering Research Program embodies several work units, one of which is entitled "Geophysical Methods for Site Characterization and Measurement of In Situ Properties." Its objective is to develop geophysical procedures that provide broader, more economic site coverage while determining more engineering parameters than before possible. In previous years, work has concentrated on developing techniques for use downstream of dams. However, safe, cost-effective design of U.S. Army Corps facilities has been limited by lack of accurate information on upstream site conditions. The need exists for development of in situ techniques for more accurately determining upstream site conditions relating to earthquake response. In view of the fact that downstream data are incorrectly extrapolated upstream, new innovative waterborne geophysical techniques must be developed to alleviate this problem. An acoustic impedance technique reported by McGee, Ballard, and Caulfield (1995), developed under the Dredging Research Program, appears ripe for further development for this application. A technically significant upgrade to this technique is the implementation of a Biot theory approach in assessing acoustic-sediment interactions in porous, saturated media. Ramifications of the Biot theory may aid engineers in accurately assessing liquefaction potential of Corps structures. This pilot study program has been conducted to evaluate new techniques to quantitatively assess sediment conditions upstream of man-made dams.

Site Selection

Arkabutla Dam and reservoir was selected as the site to demonstrate the feasibility of upstream site characterization using waterborne acoustic techniques for a variety of reasons: proximity to the New Madrid seismic zone, existing site documentation (borings in the reservoir), support from U.S. Army Engineer District, Vicksburg, and mobilization cost. Further, Arkabutla Dam is the subject of a seismic stability analysis.

General History of Arkabutla Lake

Arkabutla Lake Project is located in northwestern Mississippi on the Coldwater River, a tributary of the Yazoo River. The dam is one of four flood control dams in the Yazoo River Basin, Mississippi. The dam is of earthfill construction,

approximately 10,700 ft long with a crown width of 40 ft. Approximately 4,460,000 cu yd of embankment materials were used in constructing the dam. Slopes are protected by riprap. Maximum height above the valley floor is 67 ft. The outlet works is located near the south abutment of the main dam. It consists of a concrete approach, three-gated control structure, transition, single-barrel conduit, chute, and stilling basin. Further detailed information, if desired, is available from the Vicksburg District.

2 Approach

The methodology used to quantitatively assess the characteristics of the sediments within Lake Arkabutla is a modified seismic reflection technique that relates the engineering properties of sediments to acoustic impedance by precisely determining the reflection coefficient at each reflection horizon. To accomplish this task, a very rigorous Biot-based geoacoustic modeling program allowing for detailed investigation of up to thirteen physical fluid/sediment properties is applied to the acoustic data. The Biot theory and how it is specifically applied within the Lake Arkabutla program is provided herein.

Acoustic Subbottom Profile Data

Acoustic subbottom profile data (SBP) were collected at 1- and 4-kHz frequencies to map sediment conditions throughout the survey. Figure 1 is an example of subbottom imagery from Lake Arkabutla. It graphically shows the capability of subbottom profiling in providing stratigraphic and lithological assessment of bottom and subbottom sediment environments.

As the transmitted acoustic signal travels downward through the water column, reflections are generated at boundaries between two layers of differing material properties. In Figure 1, reflections are detected at the lakebed and in the subbottom at stratigraphic interfaces. This reflection record is actually from the approach channel to the dam outlet works. It shows recent sediment accumulation since lake formation as well as relic streambed sedimentation represented by the deeper reflection horizons.

A more typical subbottom image from Lake Arkabutla, Figure 2, shows an east-west survey line starting above the riprap blanket at the toe of the dam. Surveying away from the dam, a layer of unconsolidated sediment overlays an acoustically impenetrable horizon probably comprised of the native soil prior to dam construction.

These data are geocoded with accurate position data allowing for delineation of the horizontal and vertical extents of all unique sediment units. Another feature of these data is the contrasting colors (yellow to red color ramp) representing relative echo intensity. The higher the contrast, the greater the change in material properties. For example, a hard bottom would cause a high intensity (red to black) echo whereas the echo from a soft muddy bottom would be a low intensity (yellow hue). After calibration of the acoustic systems, these same data are

processed analytically to derive quantitative sediment properties such as density or porosity.

Reflectivity and Acoustic Impedance

Acoustic impedance, Z, is defined as the product of the seismic transmission velocity and the density of a material and basically represents the influence of a medium's characteristics on reflected and transmitted waves. Many geotechnical properties such as porosity, density, mean grain size, bulk modulus, etc., exhibit excellent correlation with impedance. It is possible, therefore, with data of a sufficient signal-to-noise (S/N) ratio, to predict geotechnical properties from normal reflectivity data through calculations of the sediment acoustic impedance. For example, acoustic impedance of the bottom surface sediment unit is related to the reflection coefficient derived at the water-sediment interface through the Zoeppritz equation (Zoeppritz 1919)

$$Z_2 = Z_1 \frac{(1+R)}{(1-R)} \tag{1}$$

where

Z_2 = impedance of second layer (the bottom sediment surface)

Z_1 = impedance of the overlying layer (in this case the water column)

R = reflection coefficient at water/sediment interface.

Since the sound velocity and density of water are known, Z_1 can be readily calculated. Therefore, to assess bottom impedance (Z_2) one must first accurately determine the reflection coefficient (R) at the water-sediment interface. This is computed using what is referred to in underwater acoustics as the *sonar equation*. The *sonar equation*, discussed thoroughly by Urick (1983), describes the quantitative effects on sonar equipment created by many phenomena peculiar to underwater sound production. This equation is a design and prediction tool for underwater sound applications and relates the effects of the medium, target, and equipment. The general sonar equation is given as follows:

$$S_R = SL - N_w - N_{hyd} + DI + BL + N_A \tag{2}$$

where

S_R = bottom reflection energy at receiver, db

SL = total energy of source, db

N_w = 20 x $\log_{10}$ (range, meters), db (transmission loss due to spherical spreading along the path of propagation)

N_{hyd} = receiver sensitivity, db

N_A = amplifier gain, db

DI = directivity index of receiving array, db (function of transducer beam pattern)

BL = bottom loss, db = 20 $\log_{10}$(R)

R = reflection coefficient

Bottom loss, *BL*, is evaluated by rearranging Equation 2:

$$BL = S_R + N_{hyd} - SL + N_w - N_A - DI \tag{3}$$

Since all terms on the right side of the equation are either measured directly or determined through precise equipment calibrations, *BL*, and therefore the surface reflection coefficient ($BL = 20 \log_{10} R$) and acoustic impedance (Equation 1), can be determined. If the desired result is an assessment of the bottom surface characteristics, the acoustic solution is complete. All that remains is the correlation between the acoustic parameters and physical sediment properties through geoacoustic relationships. This correlation is accomplished using a Biot-based geoacoustic modeling program.

For Lake Arkabutla, *BL* is calculated on all 4-kHz reflection data providing continuous survey line coverage of lakebed sediment conditions.

Biot-based Geoacoustic Modeling (BBSS)

The Biot theory (1956) was developed to explain acoustic behavior of saturated sedimentary materials accumulating on the seafloor. The applicability of the Biot theory to surficial marine sediments has been demonstrated by Stoll and Bryan (1970). Ogushwitz (1985) further assessed the applicability of the theory to the entire suite of sedimentary materials, from surficial materials with porosities as high as 90 percent, to well-consolidated materials with porosities as low as 1 percent.

Saturated sediment consists of a porous assemblage of sediment grains (the "skeletal frame"), whose interconnected pores are filled with water or gas (the "pore fluid"). Biot (1956) devised a theoretical model to describe the acoustic behavior in such a material. The Biot model treats both the individual and coupled behavior of the frame and pore fluid. Energy loss is considered to be caused by the inelasticity of the skeletal frame and by the viscosity of the pore fluid as it moves relative to the frame. The model predicts that sound velocity and attenuation in sediment will depend on frequency, the elastic properties of the sediment grains and pore fluid, material porosity, mean grain size, permeability, and effective stress.

Evans-Hamilton, Inc. (EHI) and Ogushwitz developed the *Biot-Based Synthetic Seismogram* (BBSS) program for conducting Biot-based geoacoustic modeling. The purpose of this program is to correlate measured acoustic responses with corresponding sediment properties. The BBSS program specifies values for 13 physical parameters describing the fluid, grains, and frame properties listed in Table 1. Ogushwitz's (1985) paper provides detailed guidelines for specifying

Table 1 Biot Model Input Parameters	
Fluid Properties	
Density of pore fluid	g/cm^3
Bulk modulus of pore fluid	$dyne/cm^2$
Viscosity of pore fluid	P
Grain Properties	
Density of sediment grains	g/cm^3
Bulk modulus of grains	$dyne/cm^2$
Shear modulus of grains	$dyne/cm^2$
Mean grain size	Cm
Frame Properties	
Porosity	Dimensionless
Dynamic permeability	cm/sec
Structure factor	Dimensionless
Pore size parameter	Cm
Complex bulk modulus of frame	$dyne/cm^2$
Complex shear modulus of frame	$dyne/cm^2$

values of these parameters within the BBSS program. EHI applied the BBSS program to the 4-khz acoustic reflection data from Lake Arkabutla, in conjunction with inferred sediment property information, to develop the geoacoustic parameters necessary to create synthetic seismograms based on the specific outputs of the BBSS program listed in Table 2. A conceptual schematic of this process is presented as Figure 3.

Table 2
Biot Model Acoustic Property Outputs

Properties	Units
Wave speed	M/SEC
Absorption	DB/M
Impedance	MKS
Reflection Coefficient	None
Signal Amplitude	Volts
Phase	Degrees

Assessment of Sediment Properties within BBSS

As shown in Figure 3, acoustic impedance, Z, has been related to sediment bulk density. Within the skeletal frame parameters, porosity and the frame modulii (Table 1) are the dominant properties affecting wave propagation in water-saturated sediments (Ogushwitz 1985). Estimates of the fluid and grain properties were arrived at based on standard water properties and from limited core data, respectively. The elastic constants and porosity values were then

iterated to produce synthetic seismograms matching the actual recorded data. A relationship was then developed between measured acoustic impedance and bulk density based on the relation between porosity and specific gravity. The density function shown in Figure 3 is the same relationship used for the Lake Arkabutla study.

3 Survey and Equipment

Survey

A 1000-ft swath of high resolution subbottom profile (SBP) data, sidescan sonar (SSS) data, and high frequency bathymetric data were collected along the entire north/south (N/S) length of the upstream side of Arkabutla Dam. Figures 4 and 5 present actual survey track lines for the 1- and 4-kHz geophysical systems, respectively. 4-kHz SBP data were collected along three parallel N/S transects approximately 500 ft apart, and thirty-three East/West transects at approximately 200 ft apart. This provides a balanced matrix of data for producing an accurate spatial representation of lakebed sediments. Additionally, 1-kHz SBP data were collected along the two easternmost survey lines. SSS data were collected along the three N/S 4-kHz tracklines to continuously map lakebed features and structural appurtenances to the dam.

The survey was conducted on March 29 through 31. Weather conditions were rain with brisk wind producing 0- to 1-ft wind chop on the reservoir.

Instrumentation

Due to acoustic interference between systems, the subbottom and SSS surveys were conducted independently. All geophysical data were directly interfaced with the survey vessel's positioning system. Specific instrumentation is listed in Table 3. A brief description of each instrument is provided below.

Survey vessel

The survey was conducted aboard the survey vessel *Nancy Kay* owned and operated by DIMCO, Inc., Vicksburg, MS. The survey vessel is shown as mobilized for the Arkabutla Lake survey in Figure 6.

Navigation

A Starlink Differential Global Positioning System (DGPS) was used for positioning. Real-time differential corrections were obtained from nearest Coast Guard beacon installation, improving horizontal positional accuracy to less than

Table 3
Instrumentation

System	Model	Comments
Navigation	Starlink GPS	Differential GPS with approximately ±2 m accuracy
Navigation Software	HYPACK	Position logging and survey control for all systems
High-frequency echosounder	Ross Laboratories Smartsounder	200 kHz
Sidescan sonar	EG&G SMS-260TH W/272-TD Tow fish	100- and 500-kHz dual frequency sonar system
High-resolution subbottom profiling (SBP) system	Datasonics SBP-5000	4- and 7-kHz operations
Digital Acquisition System	Triton Isis Data Acquisition and Processing System	Dual processor high-speed acquisition system used to collect all geophysical data.

±2 m RMS. Survey navigation, control, and data acquisition was accomplished using the HYPACK surveying package by Coastal Oceanographics. This system received data from the DGPS and fathometer, performed the appropriate geodetic transformations, and then transmitted corrected position and depth information to other instrument packages, such as the Isis system, aboard the *Nancy Kay*. Coordinates used for this investigation are UTM, Zone 15, and are in units of survey feet.

Subbottom profiler

The higher-frequency acoustic subbottom reflection records were generated using a Datasonics SBP-5000 high-resolution "pinger" system. The system was operated at 4-kHz to optimize for resolution and depth penetration beneath the upper lithological unit. To identify the acoustic data basement, a lower frequency acoustic system referred to as a 'boomer' operated below 1-kHz was used concurrently. These low-frequency data have poor vertical resolution but allow for greater depth of penetration than the pinger system. No statistical data analyis was performed on the boomer data, however, the data proved critical in verifyng data basement.

Sidescan sonar

An Edgetech Model SMS-260TH image correcting sidescan sonar system with a dual frequency (100- and 500-kHz) transducer tow fish was used for all sidescan operations. The system was operated at 500-kHz with a range of 75 m per side. Figure 7 shows the Model 272-TD dual frequency tow fish being deployed over the bow of the *Nancy Kay*. Sonar data were provided directly to the shipboard Edgetech graphic recorder and in analog form to the ISIS digital acquisition system for real-time quality control, display, and data storage. Figre 8 shows all acquisition system components aboard the *Nancy Kay*.

Digital data acquisition system

The ISIS shipboard data acquisition and image processing system was used to acquire, store, and process all subbottom and side scan data. The Isis system also acts as an interface between the navigation and geophysical systems providng real-time geocoding of all data. Multiple channels of data were recorded with 16-bit analog to digital converters operating through multiple sessions of Isis. The system was capable of acquisition rates of nearly 33 kHz per channel. Graphic displays (see Figure 8) provided real-time quality control of all data during acquisition.

4 Data Processing and Mapping

Acoustic Reflection Data Records

Appendix A contains a copy records of the 1- and 4-kHz subbottom profile data. The survey track lines in Figures 4 and 5 include the filenames and selected ping numbers to correlate geographic location with the data plots. Filenames are shown where they begin (at ping 0) with ping numbers annotated every 400 pings. Shown along with the filename is the CDROM archive disk number on which the actual data resides (i.e., D01). Survey direction is in order of increasing ping number.

As stated in Chapter 3, subbottom data were collected at 4-kHz for the entire survey for the purpose of characterizing the uppermost sediment. To verify data basement, a 'boomer' system was operate below 1-kHz along the easternmost north-south survey line (Figure 4). For most of the survey, acoustic penetration was limited to the bottom of the uppermost sediment unit. The confining layer is inferred to be the native soil that was exposed prior to flooding of the reservoir. The boomer data did not achieve any more penetration than the 4-kHz system. Figure 9 shows a comparison between these two data sets. At both frequencies the same reflection horizon confines acoustic penetration. The only location in the survey area where considerable acoustic penetration was obtained (Figure 1) was within the banks of the approach channel to the intake structure.

Bathymetry

Data from the 200-kHz fathometer was used to create a bathymetric surface grid and contour map of the survey area. The bathymetry map (Figure 10) shows a relatively flat surface. The most significant relief variation is between 14100500N and 14101000N near the intake tower. The 20- by 20-ft resolution digital bathymetric grid was used to create isometric surfaces, sediment thickness maps and for the overlays of sediment property data and the surface feature maps.

Side Scan Sonar Mosaic

The digital SSS data were processed to create a 0.2-m resolution geocorrected digital mosaic of the entire survey area. A small version of the mosaic is presented here as Figure 11. The SSS data supports the subbottom findings showing a remarkably uniform, low backscatter reflection surface indicative of a soft, smooth, featureless lakebed. At places the more competent native materials extrude through the recent sediment deposits as shown by darker reflection patches on Figure 11. The mosaic was useful in mapping the extents of the submerged riprap blanket covering the upstream face of the dam below the water surface. Any future surveys should include full bottom SSS imagery to assess the spatial distribution of surficial sediment conditions.

Figure 12 shows a close-up view of the intake appurtenances, i.e., wing walls, intake passages, and the bottom features in the near vicinity of the structure.

The mosaic is available as a GeoTiff image importable directly into ArcInfo GIS. No detailed interpretation of the side scan imagery was performed as part of this investigation.

5 Geoacoustic Modeling

Using calibration procedures for data with high S/N ratios, the 4-kHz acoustic reflection data were processed to provide estimates of the porosity, density, and other associated properties of the sediments found in Lake Arkabutla. Calibrations were performed to precisely assess operational parameters of the acoustic equipment. Then, in conjunction with known sediment properties, the geoacoustic parameters needed to relate acoustic impedance with porosity and density were developed. The calibrations procedures are described briefly below.

Equipment Calibration: Sources and Receivers

Equipment calibrations involve direct measurements to determine the precise transmit and receiving transducer sensitivities. Using the sonar equation (Equaion 2), determination of transmitter response and total energy at the source, source level (*SL*) , and receiving array sensitivity, N_{hydr} , was accomplished by rearranging the equation to solve for *SL*. The specific field procedures and data analysis methodology followed precisely as described in McGee et al. (1995). Table 4 lists specific equipment parameters measured for the 4-kHz acoustic reflection system. These values were used as input parameters to the BBSS geocoustic-modeling program for scaling of output synthetic seismograms and to the bottom sediment analysis program (BSED51) used for inversion of the acoustic reflection data to sediment properties.

Table 4
Equipment Parameters: SBP-5000

Frequency, kHz	4
Output Attenuation, dB	-10
SIU Attenuation Setting	2
Pulse Length, ms	0.2
Wavelet Sample Bin Size	22
Source Level, SL, dB re 1 dyne/cm^2	100
Receiver Sensitivity, N_{hydr}, dB re 1 dyne/cm^2	-72

Determination of Bottom Loss and Surface Reflection Coefficient

Characterization of the sediment surface begins by evaluating the acoustic bottom loss, BL, according to Equation 3. By substituting into Equation 3 the equipment parameters from Table 4 (*SL* and N_{hydr}, N_w, and *DI*), and evaluating the surface data throughout the survey area, a contiguous assessment of sediment acoustic response is accomplished. The acoustic solution for the bottom sediments is now complete. For the surface data, the remaining task involves correlation of acoustic response to sediment properties, hence establishing the geoacoustic calibration. All geoacoustic assessments are primarily related to the acoustic impedance, Z_2.

Biot Modeling

Biot parameters

As stated in Chapter 2, EHI developed the BBSS program for conducting Biot-based geoacoustic modeling to correlate measured acoustic responses with in situ sediment properties. These properties are typically confirmed through sediment core analysis. Specific implementation of the program is through a framework of forward modeling requiring correlation of predicted acoustic responses based on specified sediment conditions with actual measured acoustic returns. Known or inferred sediment parameters (Table 1) are used as inputs to the model and the desired quantities are manipulated to give a matching seismic response to the actual acoustic data (Table 2). Verification is provided by coring and sample analysis. For the Arkabutla study, very limited sediment data were available. Core data, included in Appendix B, provided soil and sediment properties in terms of the Unified Soil Classification System, i.e., soil type, Atterburg limits, moisture contents, etc., but no laboratory measurements of any of the thirteen physical Biot parameters. Although quantitative property information was not available, the information did provide general constraints within which the Biot theory could be used in a predictive mode.

Sediment categorization

Table 5 presents the basic categories used to report sediment conditions in Lake Arkabutla. Sediment categories are grouped according to a density range associated with sediment types. These definitions were developed by correlating acoustic response characteristics with the available core data through the BBSS program. Given the lack of sample data, sediment bulk density is considered the most reliable sediment parameter to predict. Sediment density is closely related to the elasticity of the sediments and can be calculated from acoustic impedance; a parameter that represents the influence of the medium's characteristics on reflected and transmitted waves. For all categories density is the most accurate to derive acoustically and best represents insitu conditions.

Table 5
Sediment Description

Density, g/cm³	Basic Sediment Description
< 1.2	Fluidized mud, very soft
1.2 - 1.4	Unconsolidated mud, saturated clay, silt
1.4 - 1.7	Clay-silt, clay-silt-sand mixtures
1.7 - 2.0	Stiff clayey sand, silty sand, fine sand
2.0 - 2.2	Dense clays, unsaturated sediments, possible organics
N/A	Riprap blanket

For this discussion, fluid mud is defined as sediments with density values less than 1.2 g/cm^3. Sediments below 1.2 g/cm^3 possess physical properties typical of fluidized unconsolidated sediments. These sediments were modeled with porosities greater than 0.85 and negligible frame and shear modulii (specific modeling results are discussed later. Sediments in the 1.2 - 1.4 g/cm^3 range responded geoacoustically as an inelastic frame (reasonable frame modulii) and have physical properties representative of freshwater clays and silts.

The sediments with densities higher than 2 g/cm^3 are potentially dense clays or even unsaturated sediments present before the filling of the reservoir. As will be shown in the next section, acoustic responses from these sediments were often outside the response range typical of marine sediments.

Modeling results

After reviewing all the data, three sites were chosen to represent the different acoustic environments found underneath Lake Arkabutla. These sites were selected to demonstrate the ability of the technique to meet the objectives of this investigation as well as its potential limitations.

Site Ark16a. This site is located immediately upstream (east) of the intake tower within the confines of a submerged entrance channel along survey file AR040016 in Figure 5 (refer also to Figure 24 for actual location). Figure 1 is the actual 4-kHz subbottom profile data from which the model site was selected. The model site was chosen near the area of deepest acoustic penetration. As can be seen by this reflection profile (Figures 1 and 24), nearly 17 ft of acoustic penetration was achieved at 4-kHz. It is likely this feature was part of the relic channel where erosion and depositional cycles occurred prior to filling the reservoir. An actual acoustic signal representative of this depositional environment is shown in Figure 13.

A five-layer model (water column plus four sediment layers) was required to match the data. An acceptable calibration (Figure 13), requires that actual and predicted signal amplitude and phase match accordingly. The synthetic seismogram (red line in Figure 13) is produced after convolution of a field-measured source wavelet (accomplished during equipment calibration) with the reflection

sequence modeled according to Biot theory. Table 6 presents the specific input parameters required for the BBSS model.

Table 6
Biot Model Geoacoustic Input Parameters; Site Ark16a

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Label	Water	Soft Mud	Clay-silt-sand	Sand-silt-clay	Consolidated Sediment
Travel Time to bottom of layer, ms	12.20	13.30	16.15	18.54	N/A
Fluid					
Fluid Density, g/cm^3	1.0	1.0	1.0	1.0	1.0
Fluid Bulk Modulus, dynes/cm^2, xE+11	0.215	0.215	0.215	0.215	0.215
Fluid Viscosity	0.019	0.019	0.019	0.019	0.019
Grain					
Grain Density, dynes/cm^2		2.53	2.65	2.65	2.65
Grain Bulk Modulus (Real), xE+11		5.40	4.50	4.50	3.64
Grain Shear Modulus (Real), xE+11		2.70	2.10	2.10	1.80
Mean Grain Size, cm		0.0016	0.0062	0.016	0.016
Frame					
Porosity		0.84	0.55	0.47	0.36
Permeability, cm/sec, xE-05		0.04	0.003	0.0007	0.00006
Frame Bulk Modulus (Real), dynes/cm^2, xE+09		No Frame	2.50	2.50	102.0
Frame Bulk Modulus (Imag), dynes/cm^2, xE+09		No Frame	0.027	0.027	1.12
Frame Shear Modulus (Real), dynes/cm^2, xE+09		No Frame	1.15	1.15	47.0
Frame Shear Modulus (Imag), dynes/cm^2, xE+09		No Frame	0.037	0.037	1.50

Sediment layers range from soft muddy sediments to a dense, high impedance layer considered the acoustic 'basement.' The soft mud blankets the lakebed and is found throughout the survey area. This mud represents recent deposition and shows properties typical to unconsolidated fine-grained sediments. This layer was modeled with negligible frame and shear bulk modulli which account for the lack of shear strength normally found in consolidated sediment materials. Porosity was determined to be 0.84 and wave velocity and acoustic impedance 1429 m/sec (indicates near saturation) and 1778 mks, respectively.

Underlying this soft mud layer is a unit of clay/silt/sand (Table 6, Layer 3) with a porosity of 0.55. This results in a high-impedance contrast with the upper layer. Wave velocities increased to 1539 m/sec. Average bulk density modeled at 1.74 g/cm^3.

Beneath the clay/silt/sand unit is a more competent layer (Table 6, Layer 4). An increase in density from 1.74 g/cm^3 to 1.87 g/cm^3 could result from a higher percentage of sand in the material.

A high impedance layer (> 6300 mks), represented by the high-amplitude reflector in Figure 13, is the confining acoustic interface and was modeled as a consolidated sediment with very high frame bulk and shear modulli (Layer 5 in Table 6). Polarity of the reflection coefficient remained positive indicating an increasing impedance environment (i.e., a harder material than the overburden sediment). No penetration was achieved below this layer with any of the acoustic systems.

The sediment cores did not provide enough information to establish absolute verification of the model. However, based on past experience and general guidance regarding the likely sediment environment at Lake Arkabutla, the results should be considered reasonable estimates of actual conditions. Except for pockets of trapped gas (i.e., organics) and consolidated, unsaturated sediments, estimates of the acoustic responses (impedance, velocity, phase, and reflection coefficient) should be accurate.

Site Ark14a. This site represents a potential difficulty in using normal-incidence reflection techniques where the sediments were previously exposed native soils submerged after filling of a reservoir. Figure 2 from Chapter 1 is the profile data from line 14 and shows a soft mud layer overlying a highly reflective and acoustically impenetrable layer at Model site Ark14a (actual location shown in Figure 23). Figure 14 shows the upper sediment unit modeling as a soft mud identical to the uppermost unit model at site. Acoustic penetration is arrested at the bottom of this soft mud unit. Specific BBSS input provided in Table 7 does not list any sediment data for Layer 3. Attempts to model the actual data failed when using saturated sediment parameters. The matching response shown in Figure 14 was obtained by establishing the bottom boundary of the model at this interface and setting the reflection coefficient to -0.80. The large negative reflection coefficient indicates a decreasing impedance sequence and a drastic change in sediment type. Normally, this would be caused by gas bubbles trapped in the sediments. However, the fact that this area was most likely exposed pasture lands prior to flooding the reservoir, the acoustic response could indicate very low moisture content clays similar to hardpan. Either of these conditions could preclude one's ability to achieve sufficient penetration into these materials, particularly at 4-kHz. Also, this modeling technique is only valid in gas-free saturated sediments and could be a limiting factor at other sites regardless of seismic frequency.

Site Ark14b. This site is located approximately 200 ft past the end of the riprap blanket covering the toe of the dam (Figure 2 and Figure 23) along a short shelf that is possibly an engineered extension of the upstream face of the dam. These data indicate a more fully saturated sediment environment conducive to modeling hydroacoustic data. There are no measured subbottom reflectors in the vicinity of site Ark14b (Figure 2). Model comparison is presented in Figure 15 and the input parameters are listed in Table 8. The sediment models as a stiff clay/silt material with a porosity of 0.58, density of 1.64 g/cm^3, and reasonable frame bulk and shear modulli. The data are 'in-phase' with the source wavelet indicating a 'gas-free' environment. The core data (Appendix B) were taken in the vicinity of this site, i.e., near the toe of the dam, and show sands and clays with relatively low blow counts supporting the model predictions.

Table 7
Biot Model Geoacoustic Input Parameters; Site Ark14a

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Label	Water	Soft Mud	Basement: Organic/ Unsaturated	Not Used	Not Used
Travel Time to bottom of layer, ms	9.13	9.98			
Fluid					
Fluid Density, g/cm^3	1.0	1.0			
Fluid Bulk Modulus, dynes/cm^2, xE+11	0.215	0.215			
Fluid Viscosity	0.019	0.019			
Grain					
Grain Density, dynes/cm^2		2.53			
Grain Bulk Modulus (Real), xE+11		5.40			
Grain Shear Modulus (Real), xE+11		2.70			
Mean Grain Size, cm		0.0016			
Frame					
Porosity		0.84			
Permeability, cm/sec, xE-05		0.04			
Frame Bulk Modulus (Real), dynes/cm^2, xE+09		No Frame			
Frame Bulk Modulus (Imag), dynes/cm^2, xE+09		No Frame			
Frame Shear Modulus (Real), dynes/cm^2, xE+09		No Frame			
Frame Shear Modulus (Imag), dynes/cm^2, xE+09		No Frame			

Table 8
Biot Model Geoacoustic Input Parameters; Site Ark14b

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5
Label	Water	Stiff Clay/Silt	Not Used	Not Used	Not Used
Travel Time to bottom of layer, ms	7.47	N/A			
Fluid					
Fluid Density, g/cm^3	1.0	1.0			
Fluid Bulk Modulus, dynes/cm^2, xE+11	0.215	0.215			
Fluid Viscosity	0.019	0.019			
Grain					
Grain Density, dynes/cm^2		2.65			
Grain Bulk Modulus (Real), xE+11		5.40			
Grain Shear Modulus (Real), xE+11		2.70			
Mean Grain Size, cm		0.0016			
Frame					
Porosity		0.58			
Permeability, cm/sec, xE-05		0.003			
Frame Bulk Modulus (Real), dynes/cm^2, xE+09		2.50			
Frame Bulk Modulus (Imag), dynes/cm^2, xE+09		0.027			
Frame Shear Modulus (Real), dynes/cm^2, xE+09		1.15			
Frame Shear Modulus (Imag), dynes/cm^2, xE+09		0.037			

Modeling summary

Three sites were modeled to describe general sediment conditions within Lake Arkabutla. Insufficient core data were available to intensively evaluate the BBSS program and to provide verification of predicted sediment types. Acoustic penetration was limited with the subbottom profiling systems used. Future survey programs should include a small sampling/coring program in conjunction with the geophysical surveys to calibrate and verify the analysis.

Given the limited ground truth data, the approach provided a method to rigorously interrogate actual sediment conditions from acoustic data. The Biot theory is a proven model. Acoustic calibration methods have been developed and employed here to quantify precisely the net acoustic response in a given sediment sequence. For data with sufficient signal response (Ark16a), the method provided reasonable estimates of sediment characteristics. The method also provided a critical evaluation of 'non-standard' sediment environments, such as site Ark14a, where it was not possible to match actual acoustic data using standard sediment parameter inputs.

Inversion of Acoustic Data

Acoustic reflection data are processed through seismic inversion techniques to produce continuous sets of geopredicted sediment property values. This is accomplished through a software package developed by EHI, the BSED51 program, designed to incorporate calibrated acoustic data with modeled geoacoustic parameters. The BSED51 program was used to process all 4-kHz acoustic data. It provides graphics and digital sediment property output files and can be delivered as input data for all visualization and CADD work. Figure 16 shows density output graphic from the BSED51 program for the water-sediment interface along survey line 14 (Figure 2). Selected porosity (β) and density (ρ) values determined from the Biot calibration have been included for comparison with surface densities computed using BSED51. It shows excellent correlation between the modeled and processed results. The red dashed-line represents detected depth at the reflection interface used in the density calculations. Detection levels are controlled by the 'Threshold' variable and is analogous in function to the sensitivity control on a standard echosounding system. Processing input parameters are listed in the green control panel on the left side of the figure, and includes equipment calibration values (Table 4), detection threshold controls, transmitter/receiver geometry, and statistical processing controls. The geoacoustic calibration function, listed as 'Mobile Bay' in the control panel, is the impedance versus density model used for the Arkabutla Lake data. This relationship was derived during the geoacoustic-modeling phase of a previous survey performed in Mobile Bay, Alabama (McGee 1998). Acoustic response was similar to this survey in that a layer of unconsolidated fine sediments, or fluid mud, overlaid more competent native sediments. All 4-kHz data were processed through the BSED51 program to create matrices of position coordinates, depth, acoustic impedance, density, and porosity.

The BSED51 program was also used to conduct inversion on selected sub-bottom reflection interfaces. Accounting for two-way transmissivity and absorption through the upper layer the reflection coefficient and acoustic impedance can be calculated for subsequent deeper layers. The geoacoustic calibration function is the same as for the water-sediment interface. Figure 17 shows the graphical output screen from BSED51 along with selected BBSS reflection coefficient , R, value for model site Ark14a. Density spikes represent acoustic responses outside the boundaries established for a natural sediment response. Conditions at these locations seem to be unsaturated or consolidated clays and silts. The presence of interstitial gasses is also a possibility.

6 Data Presentation

A brief description of physical conditions is provided to assess the spatial distribution of sediments within the surveyed portion of Lake Arkabutla. The purpose here is to present a range of possible data products available to assist in interpretations of geophysical survey data. A digital mosaic of side scan sonar imagery (Figure 11) was created to provide a contiguous picture of surficial sediment characteristics. Lakebed bathymetry data was compiled into a 20-ft by 20-ft resolution surface grid for contouring and as a base for overlays of specific sediment property information. Output from the BSED51 program was gridded for bulk density and sediment thickness to describe the actual sediment conditions. Figure 18 presents selected isometric views of sonar imagery, bathymetry, and sediment density with respect to water depth. This figure shows how this type information can be combined to provide enhanced interpretations of actual bottom conditions. For example, on the right side of Figure 18 is a small hard reflector (black contrast) near the front of the image. This corresponds to a small spike in the bathymetric data and a small high-density patch in the density image.

Lakebed Sediment Density and Thickness

Surficial sediment density was continuously mapped over the extent of the survey area (Figures 18 and 19). Density is for the entire thickness of the upper sediment unit and shows a uniformly distributed layer of 1.2 - 1.4 g/cm^3 material. Density increases nearer the toe of the dam (western edge of map). Density is not reported for the riprap placed near the toe of the dam.

For Arkabutla, and other reservoirs, these data offer a complete picture of the distribution of sediments accumulating on the bottom of the lake. Combining physical property data such as density, with sediment thickness maps, it is possible to calculate the total volume of mud accumulated. Figure 20 presents a measured thickness for the upper sediment unit. This map was developed from the subbottom profile data by combining reflection interfaces from the digital subsurface model. Except for survey line 16 near the intake tower entrance, only a single subbottom interface at the bottom of the mud layer was detected. The data was not sufficient to develop more elaborate lithological models of Lake Arkabutla.

Sediment Profiles

Six representative subbottom profile sections are presented in Figures 21 through 26. Each figure shows the actual subbottom profile data with the associated two-dimensional interpretations of lithology. This presentation is the basic 'fence diagram' format familiar to most geophysicists. The sediment units are grouped according to density range. After modeling, a basic sediment description was developed for each density range as presented in Table 5 (Chapter 5). Had there been confirming core sample data, more precise descriptions would have been developed, possibly relating to specific seismic issues. The profiles are self-explanatory and will only be briefly discussed following.

A 2- to 3-ft thick layer of soft mud overlays native soils along the eastern two-thirds of the survey area. No penetration was obtained through the native soils, resulting in a simple two-layer lithology. The western edge of the profiles extends over a riprap blanket along the toe of the dam. This zone of riprap is characterized by high-amplitude acoustic returns followed by numerous multiple reflections. Acoustic response in native soils tend to be high-amplitude with inconsistent wavelet polarity indicative of organic/gassy or unsaturated environments.

As shown by Figures 21 through 26, subbottom profiling allows for continuous surveys of subbottom conditions from which an optimum sediment sampling/coring plan can be developed assuring sampling from all sediment units. Through geoacoustic modeling of the sediment and acoustic data, physical properties can be determined for all survey data providing accurate data over large geographic areas. This would reduce or even eliminate the potential of erroneous extrapolation of sediment conditions between isolated core locations.

7 Conclusions and Recommendations

Prior to the filling of Lake Arkabutla, the area upstream of the dam was comprised of agricultural lands. The only sediments to be found were those deposited within the banks of the streams meandering through the watershed. Except for the relic streambed, the former surface soils act as the confining acoustic interface (Figure 2), limiting penetration to the bottom of the layer of sediments accumulated since filling of the reservoir. Within the meandering streambed, nearly 17 ft of acoustic penetration was achieved for the 1- to 4-kHz frequency bandwidth chosen. In these areas, sediment characterization was reasonable as shown by Figures 1, 13 and 24.

The instruments selected for this initial investigation were not adequate due to frequency and source level to overcome attenuation caused by the confining layer. This confining layer is likely comprised of compacted, unsaturated soils possibly containing decomposing organics found over most of the project site. This may be a typical configuration for man-made reservoirs. For an acoustic solution, a lower frequency system is recommended.

Specific conclusions and recommendations for the Lake Arkabutla sediment characterization feasibility study are provided following.

Conclusions

Biot theory

The Biot theory is a proven method (see references). For Arkabutla survey data with sufficient signal response, the method provided, in the absence of quantified ground truth from the core data, reasonable estimates of sediment density, porosity, acoustic wave speed and attenuation were obtained.

The method of forward modeling to develop site specific transfer functions relating acoustic response to sediment properties provided a critical evaluation of the sediment environment at Lake Arkabutla. This allowed for analysis of 'non-standard' sediment configurations.

Sediment bulk density, computed from acoustic impedance, is considered the most reliable sediment parameter for Arkabutla and best represents in situ conditions.

Core sampling

No sampling or coring was conducted in conjunction with this investigation. Core data retrieved from near the upstream toe of the dam (Appendix B) was provided from a previous investigation (reference if needed).

No laboratory measurement of any of the thirteen physical Biot parameters was available from the existing core data. This provided only general guidance from which the Biot theory could be used in a predictive mode.

Core positioning was not coordinated in conjunction with the geophysical survey nor was it possible to accurately determine their precise location.

Acoustic response

Characterization of sediments accumulated since filling of the reservoir was accomplished in terms of density and sediment thickness providing information useful in accurately determining the rate and composition of sedimentation in Lake Arkabutla. The data were collected rapidly and continuously, providing full coverage mapping of sediment conditions within the lake.

Information regarding the reflection coefficient for the water-sediment interface, attenuation through the upper sediment layer, and reflectivity of the confining layer was obtained.

Within the former riverbed, acoustic penetration and signal response was sufficient to characterize sediment conditions down to nearly 17 ft below the lake bottom using the 1- and 4-kHz systems.

An acoustically confining layer of compacted unsaturated soils limited acoustic penetration to the bottom of the sediment layer. This layer did not respond acoustically as a standard sediment. Both the 1-kHz and 4-kHz systems were unable to penetrate through this native soil unit.

Recommendations

A follow-on field study with an acoustic source operating in the seismic range, i.e., 100-500-Hz should be conducted to fully evaluate the feasibility of an acoustics approach. This would likely involve use of a small airgun source.

A ground penetrating radar (GPR) system should be included as part of the field investigation to verify the presence of acoustic-inhibiting conditions such as decomposing organics.

A coring program resulting from the geophysical investigation is recommended. Core locations should be selected based on survey results. If good core data already exists, the geophysical survey must be designed to collect acoustic information precisely over the core location.

Cores should be analyzed for density, porosity, sound velocity, and specific gravity along with a complete grain size analysis. This will provide sufficient information for calibration of geoacoustic conditions using the Biot theory.

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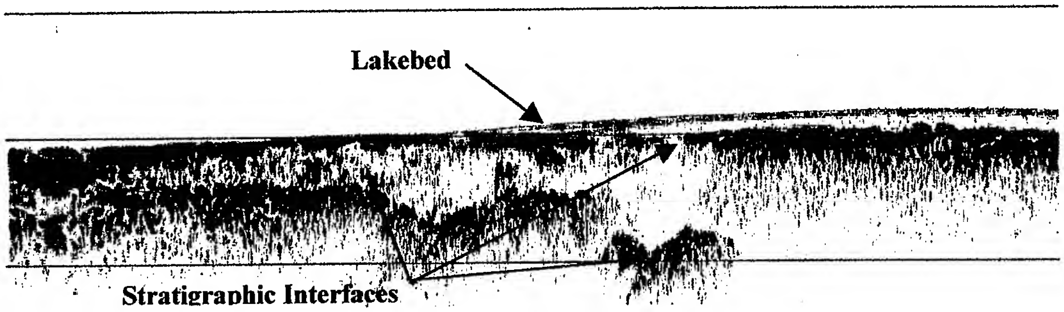


Figure 1. Example subbottom profile from Lake Arkabutla

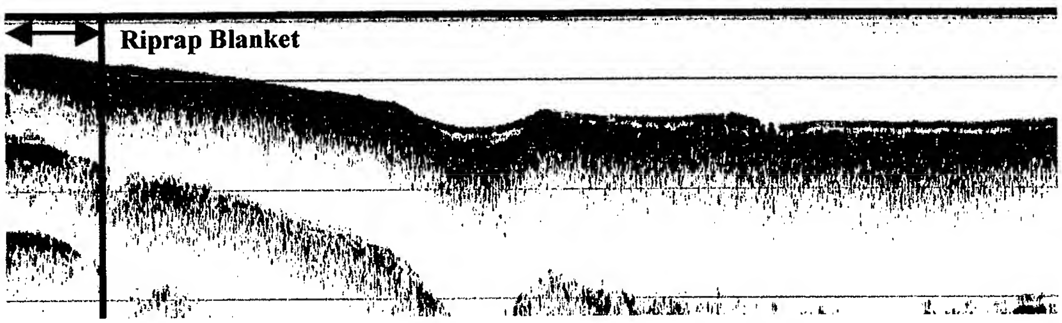


Figure 2. Typical subbottom profile data from Lake Arkabutla

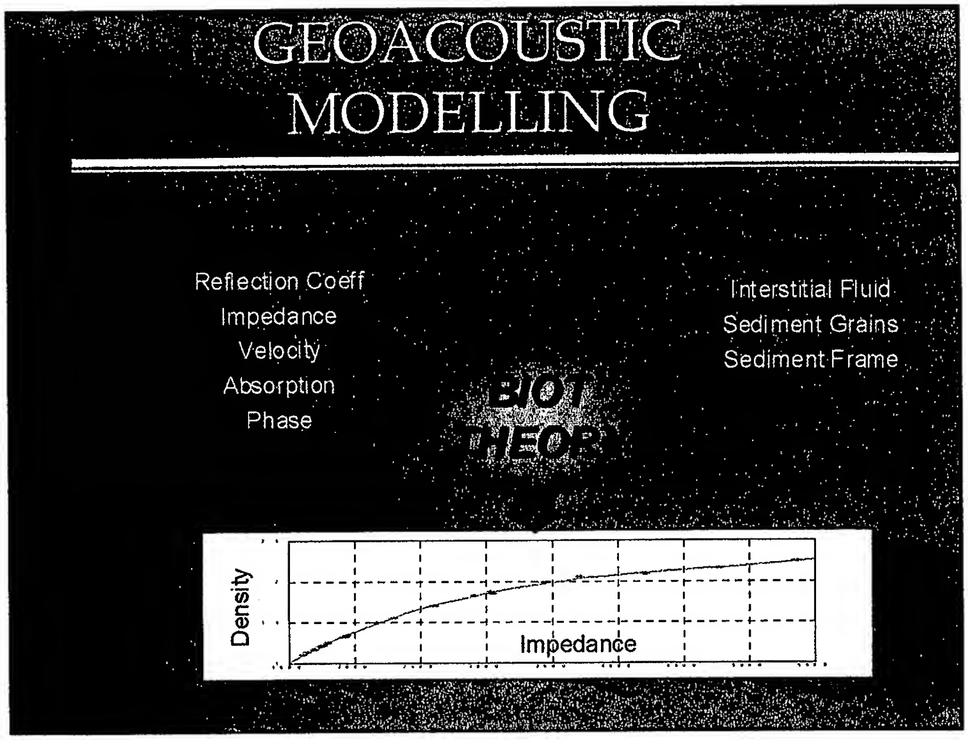


Figure 3. Biot-based modeling concept

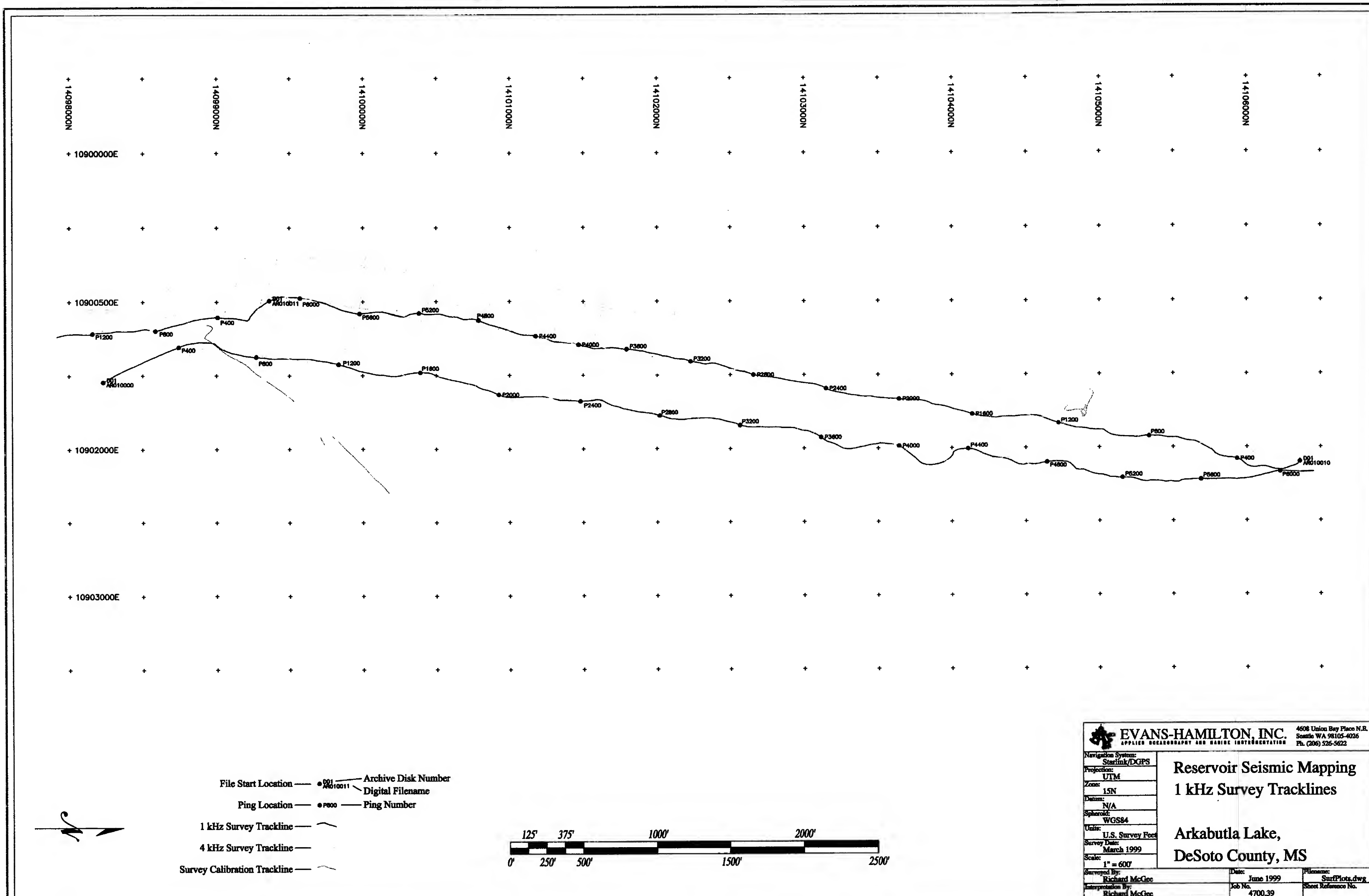


Figure 4. Lake Arkabutla 1-kHz survey track lines.

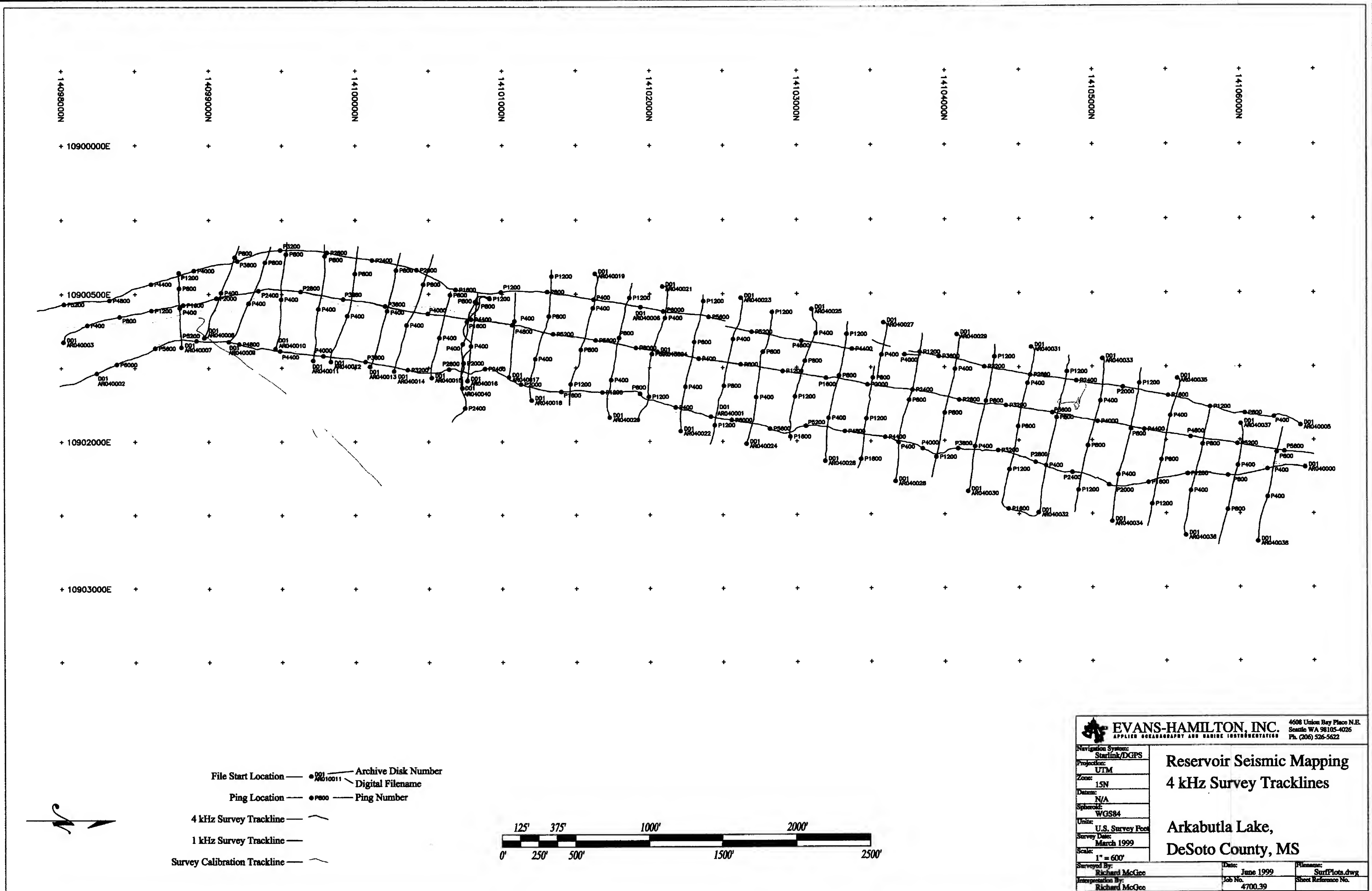


Figure 5. Lake Arkabutla 4-kHz survey track lines.

Figure 6. Survey vessel *Nancy Kay* at Lake Arkabutla

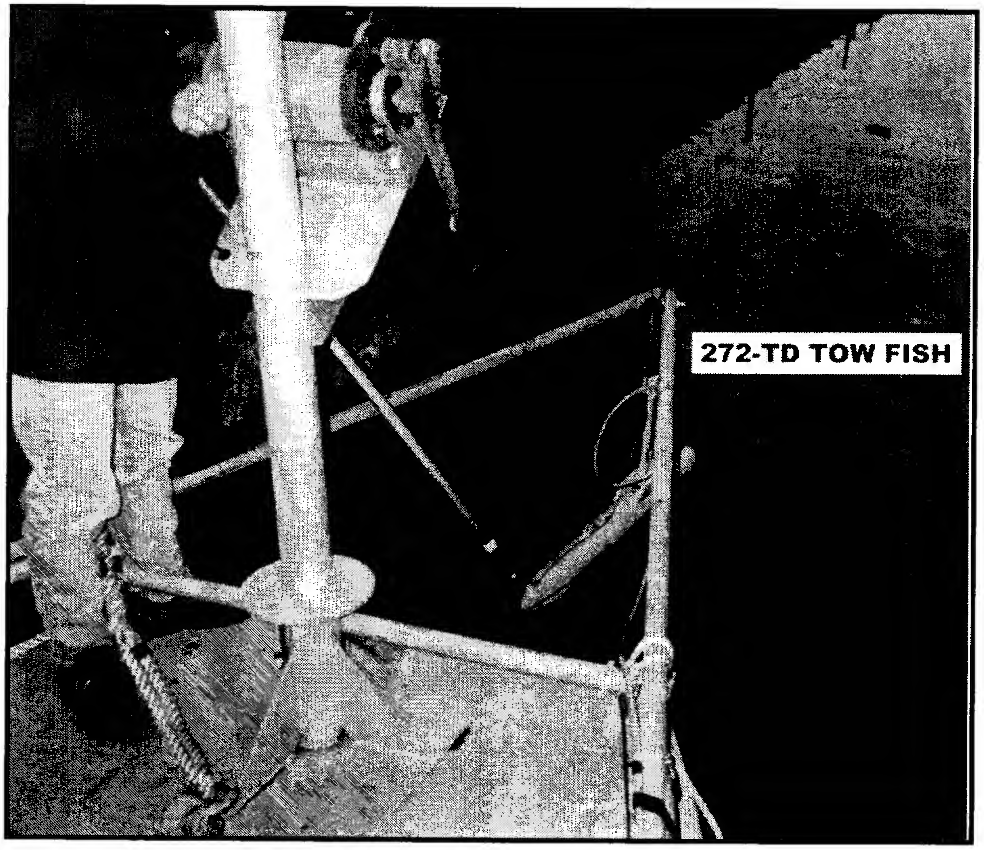


Figure 7. Side scan tow fish deployed over bow of *Nancy Kay*

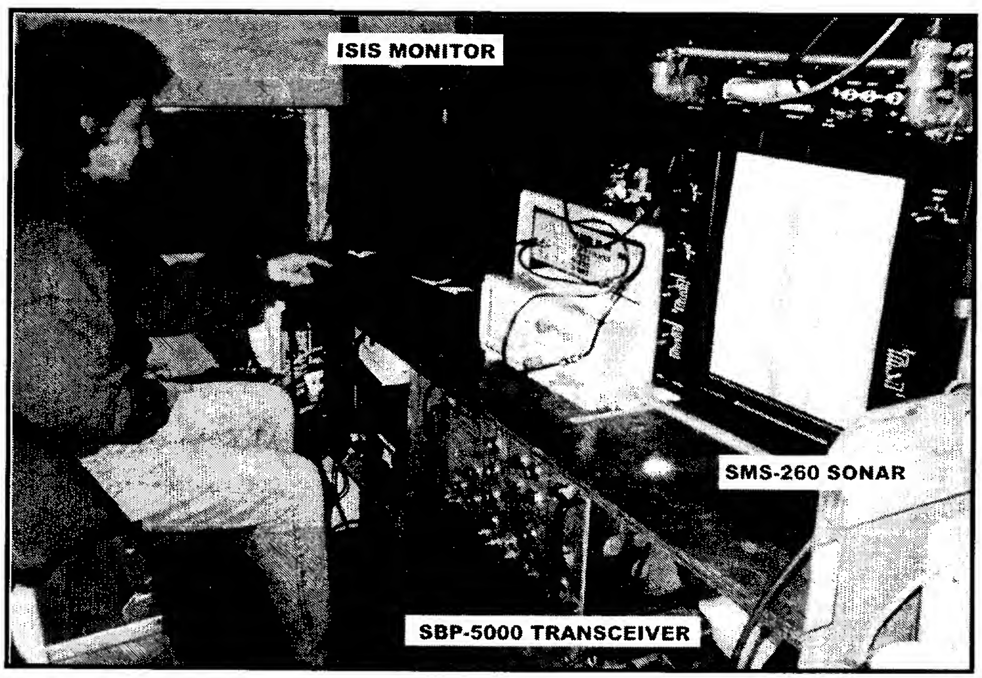
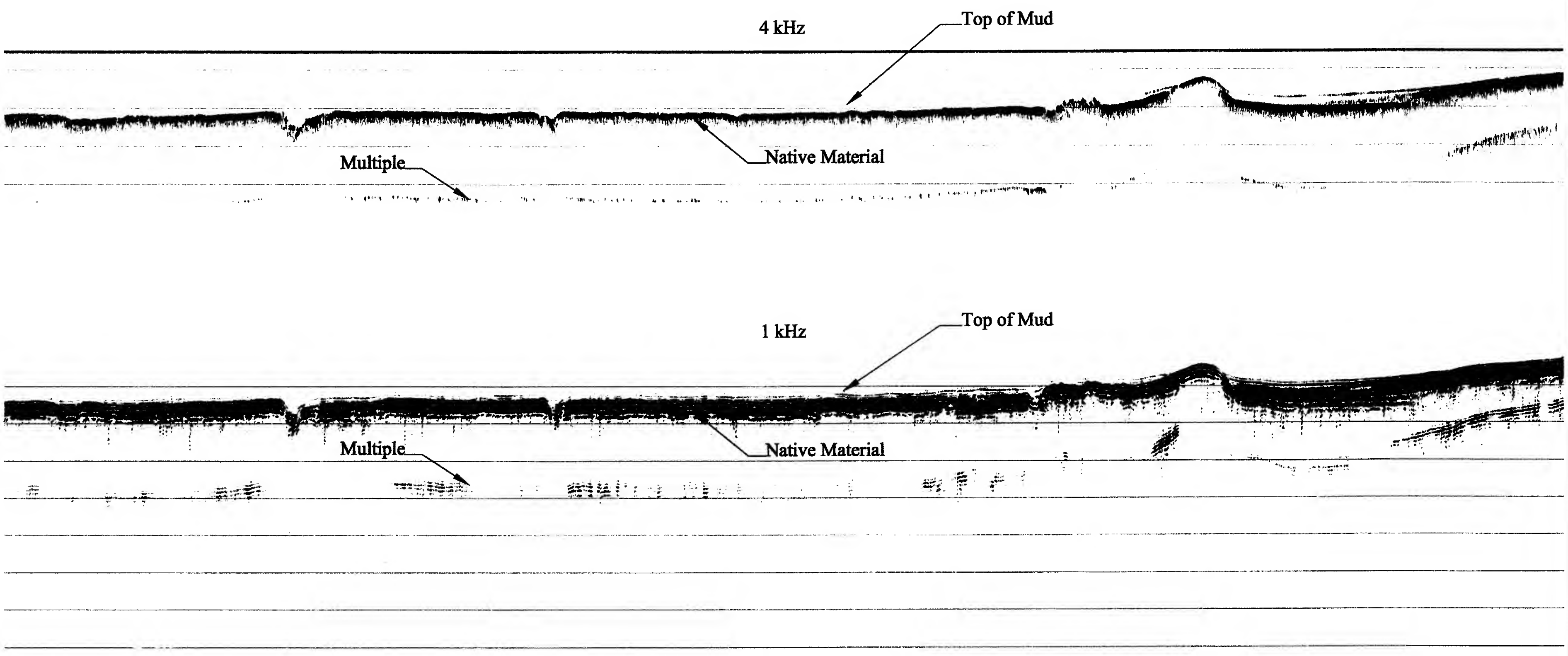


Figure 8. Geophysical data acquisition



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Navigation System: Starlink/DGPS	Reservoir Seismic Mapping Comparison of 1 kHz and 4 kHz Subbottom Profiles Arkabutla Lake, DeSoto County, MS
Projection: UTM	
Zone: 15N	
Datum: N/A	
Spheroid: WGS84	
Units: U.S. Survey Feet	
Survey Date: March 1999	
Scale: N/A	

Surveyed By: Richard McGee	Date: June 1999	Filename: SurfPlots.dwg
Interpretation By: Richard McGee	Job No. 4700.39	Sheet Reference No.
Drawn By: Kevin Redman / Brent Johnston		Plate No.
Checked By: Richard McGee		Sheet No.

Figure 9. 1- and 4-kHz subbottom profile comparison.

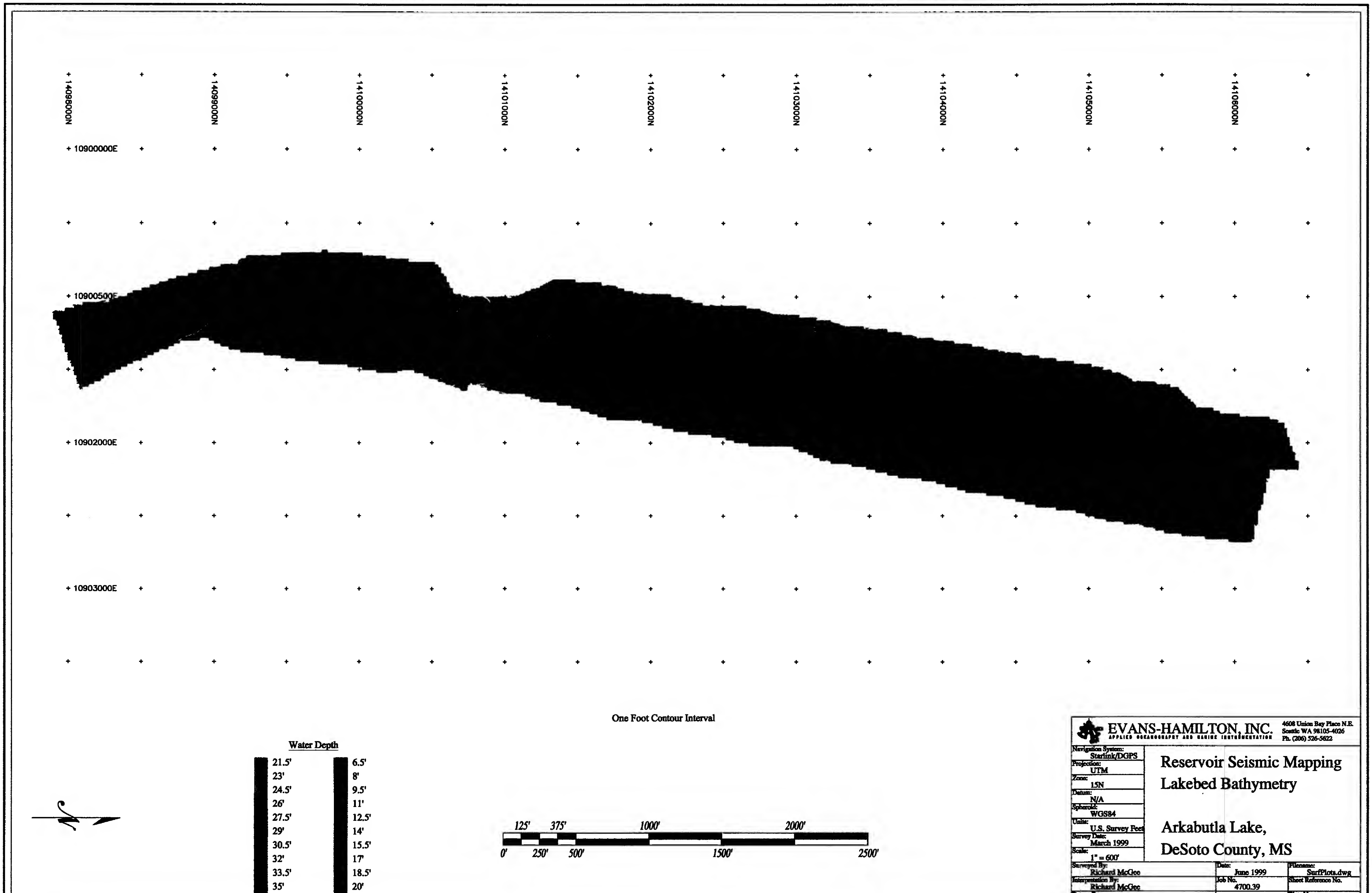


Figure 10. Bathymetry map, Lake Arkabutla.

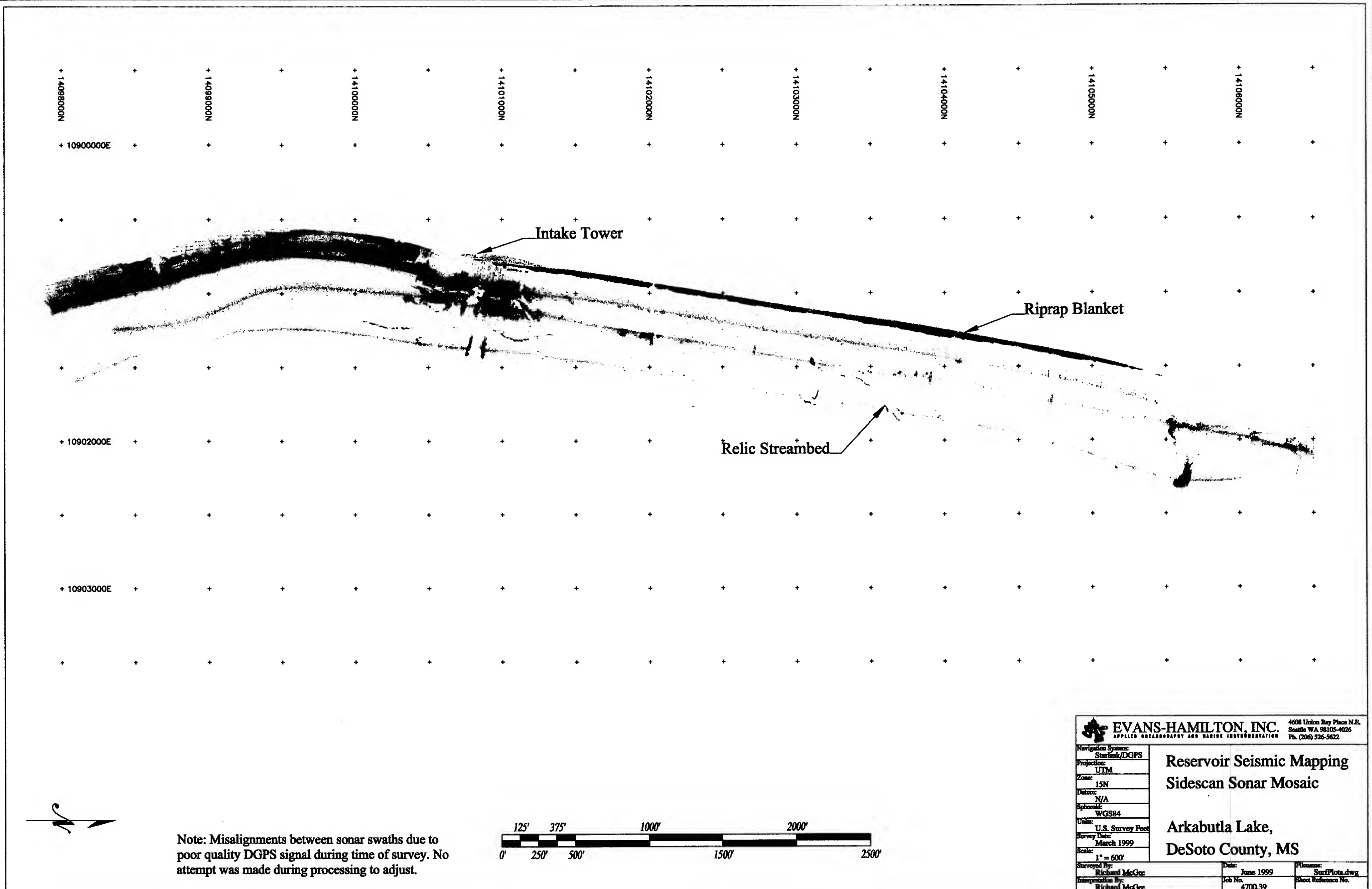


Figure 11. Side scan sonar mosaic, Lake Arkabutla.

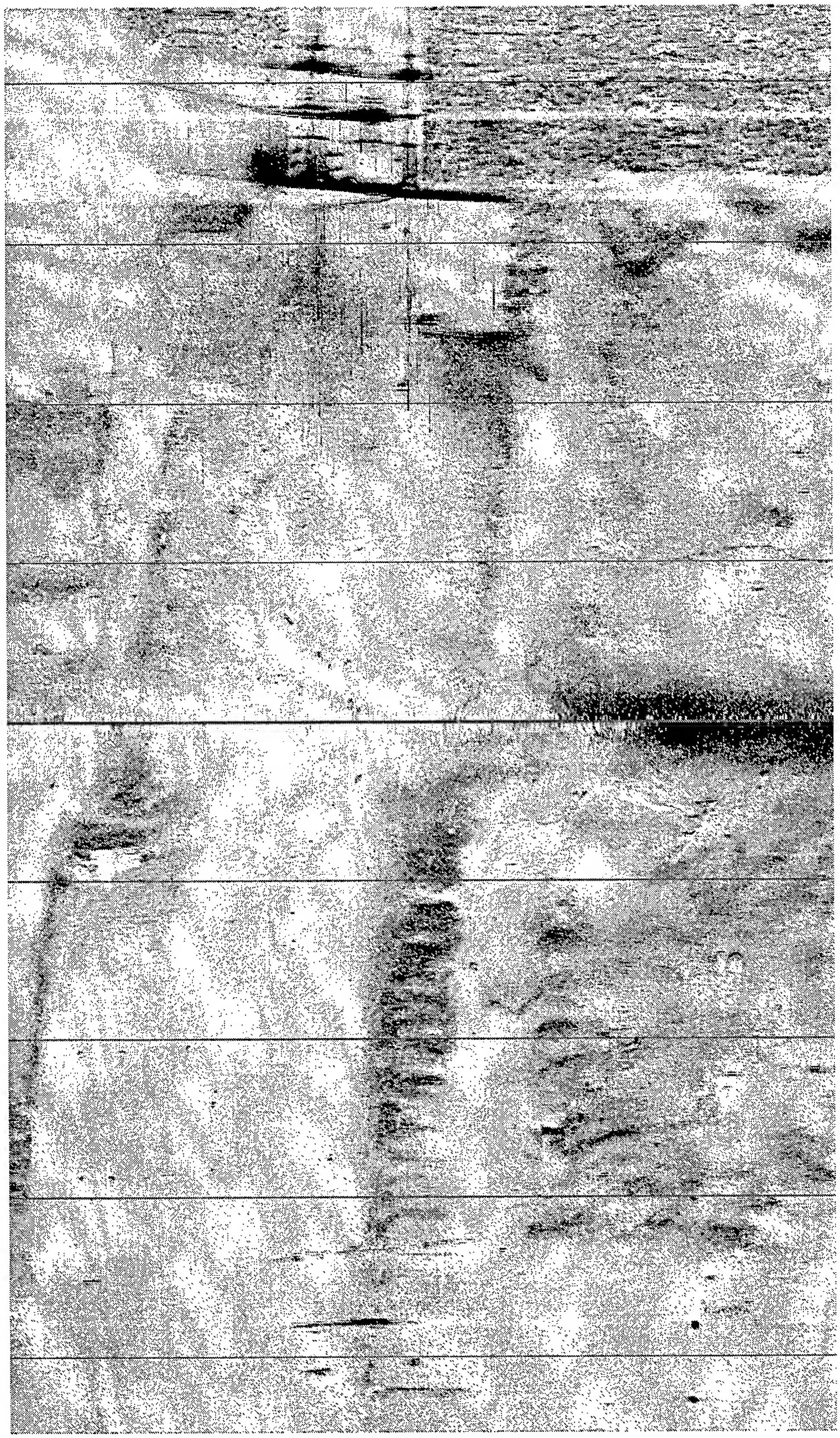


Figure 12. Side scan image of approach to intake

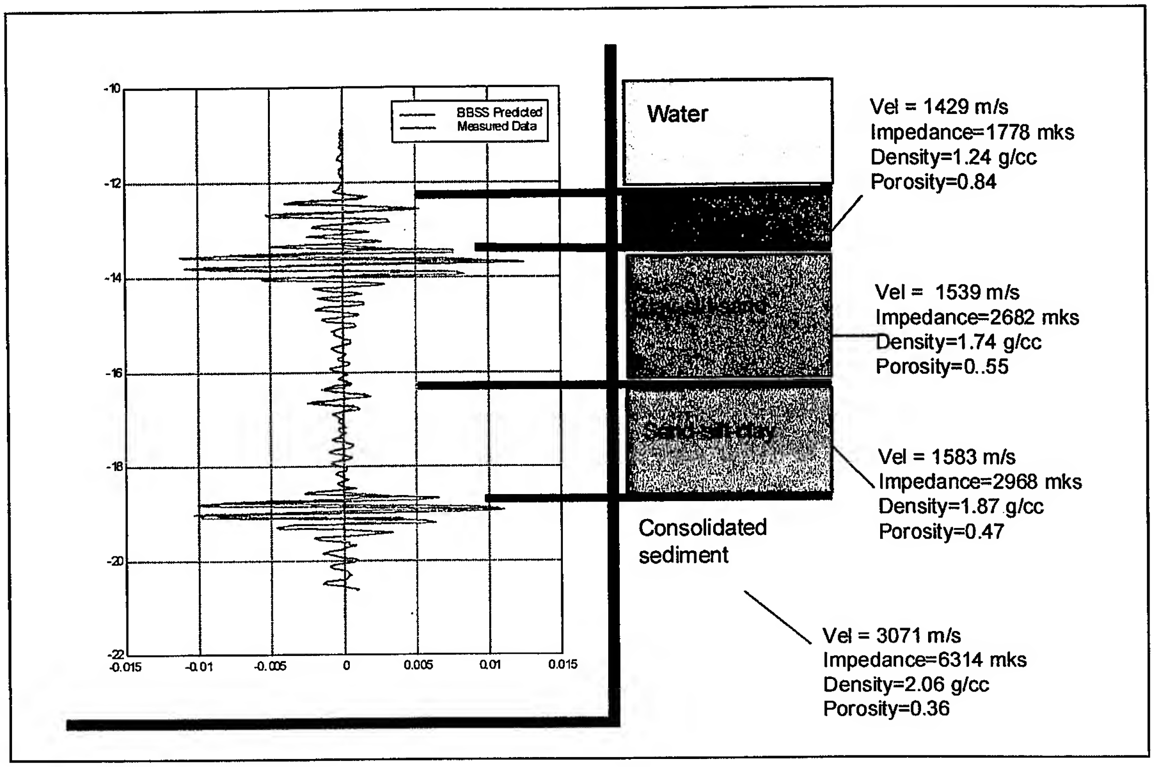


Figure 13. Geoacoustic model; Site Ark16a

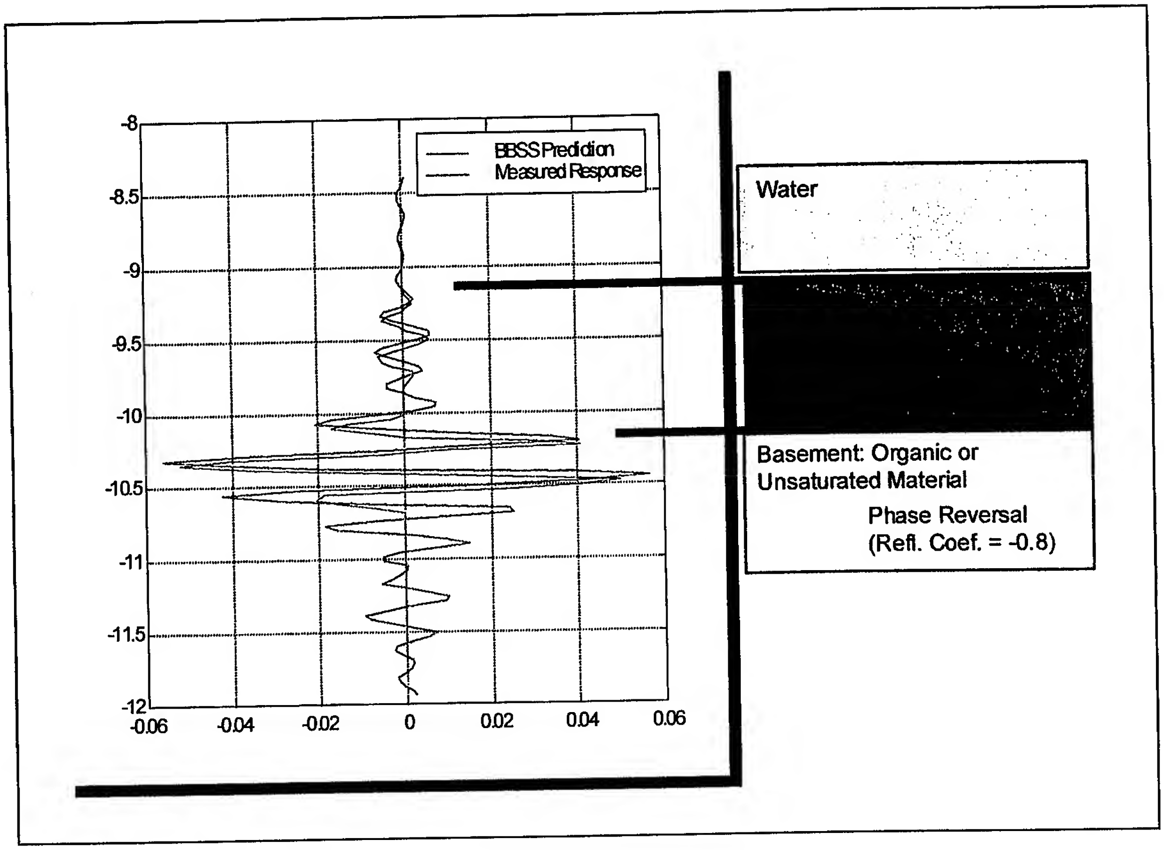


Figure 14. Geoacoustic model; Site Ark14a

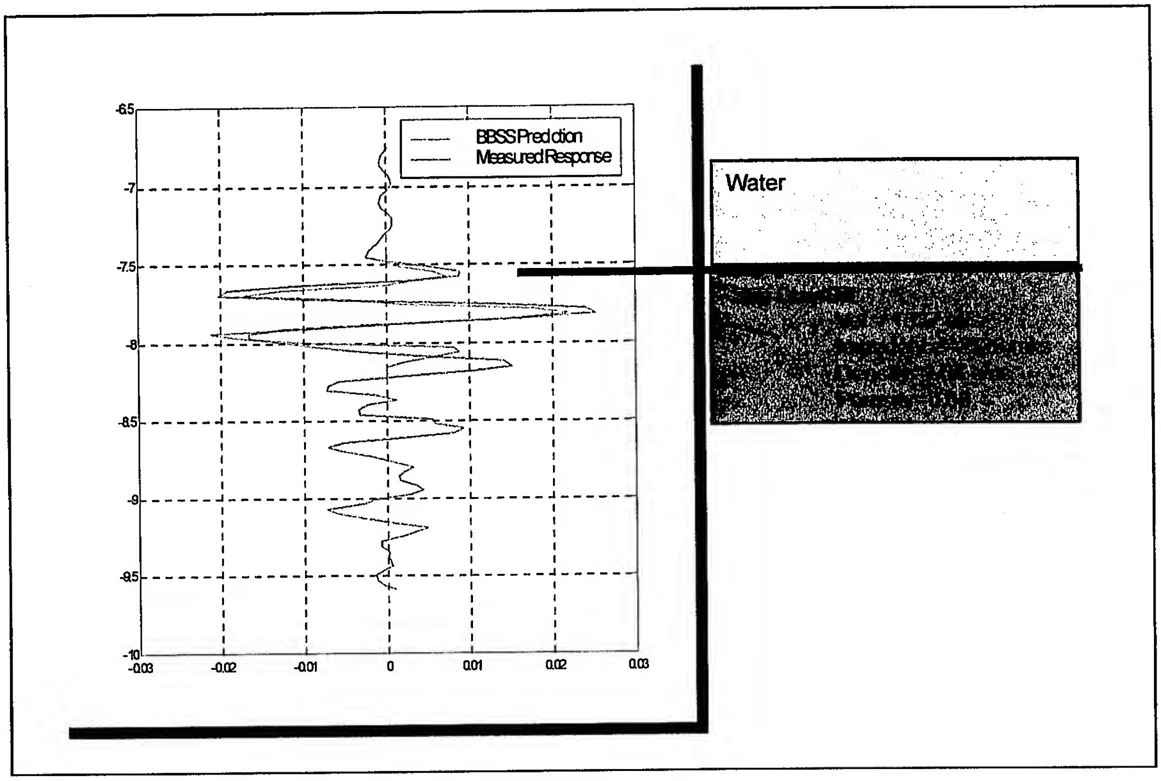


Figure 15. Geoacoustic model: Site Ark14b

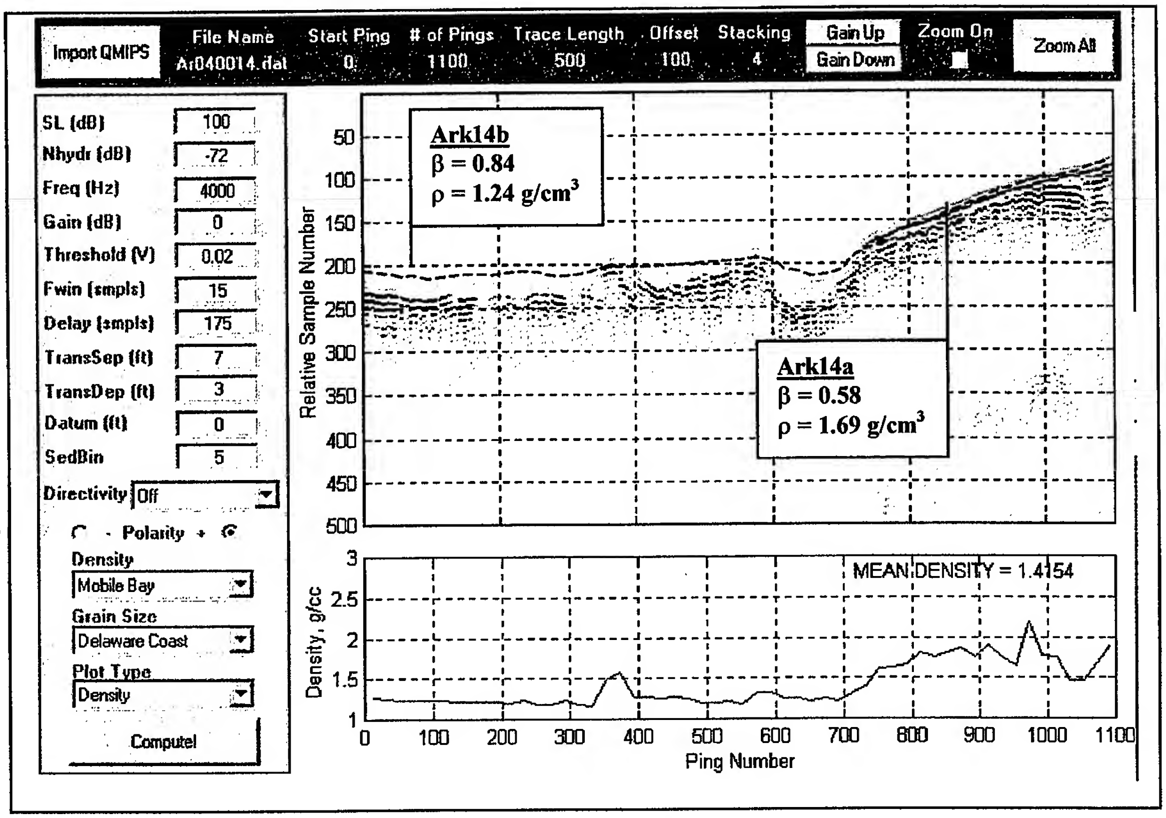


Figure 16. BSED51 output at water-sediment interface

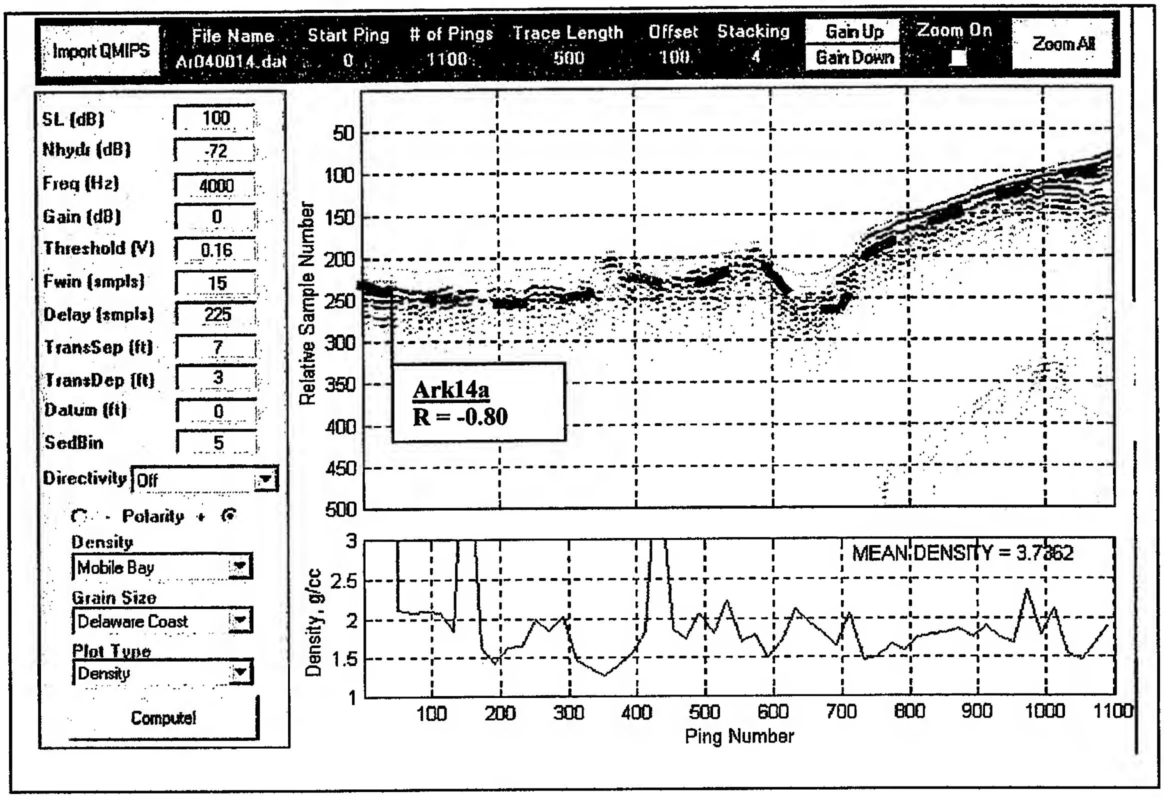


Figure 17. BSED51 output at data basement

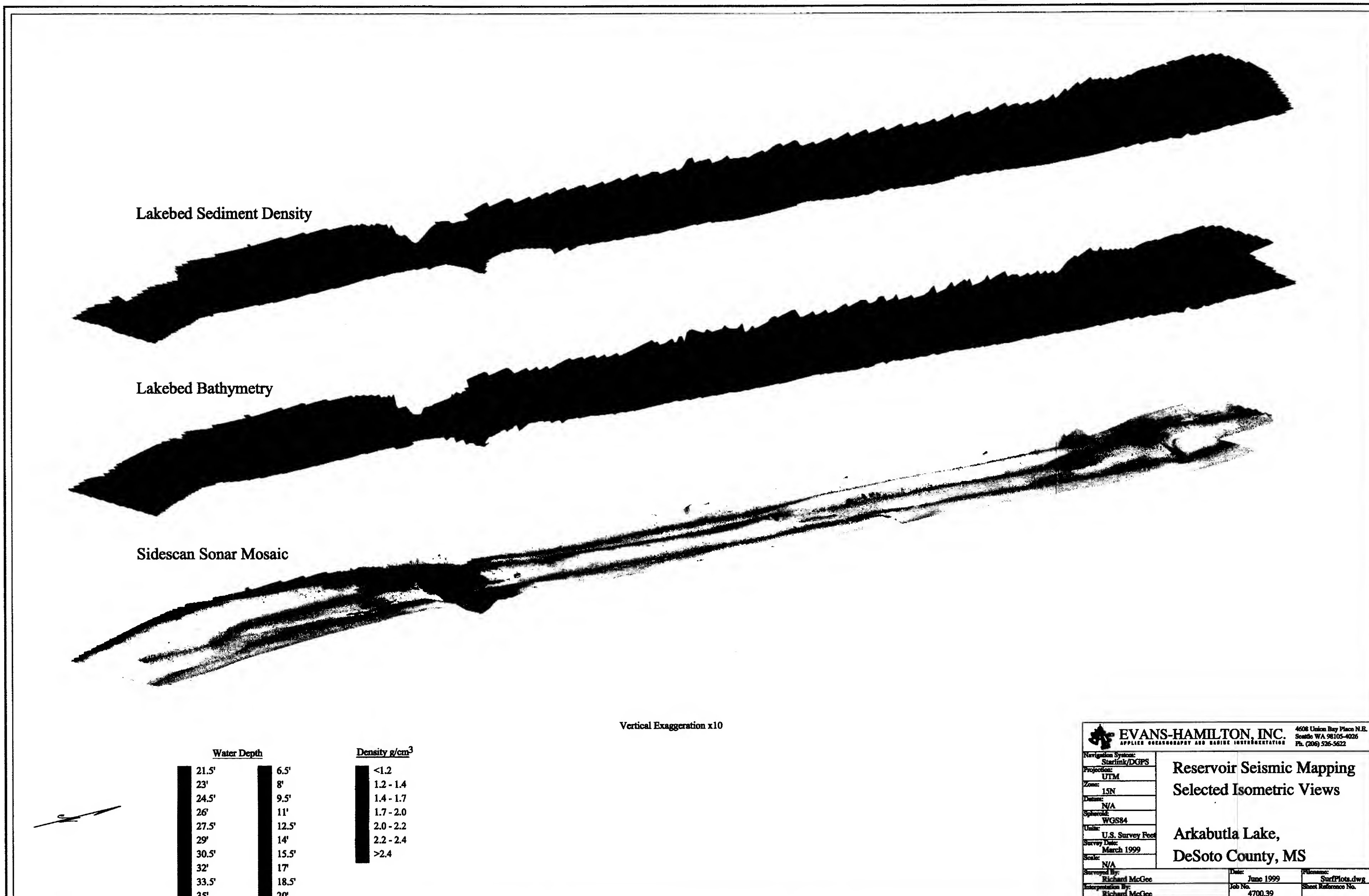


Figure 18. Selected isometric views.

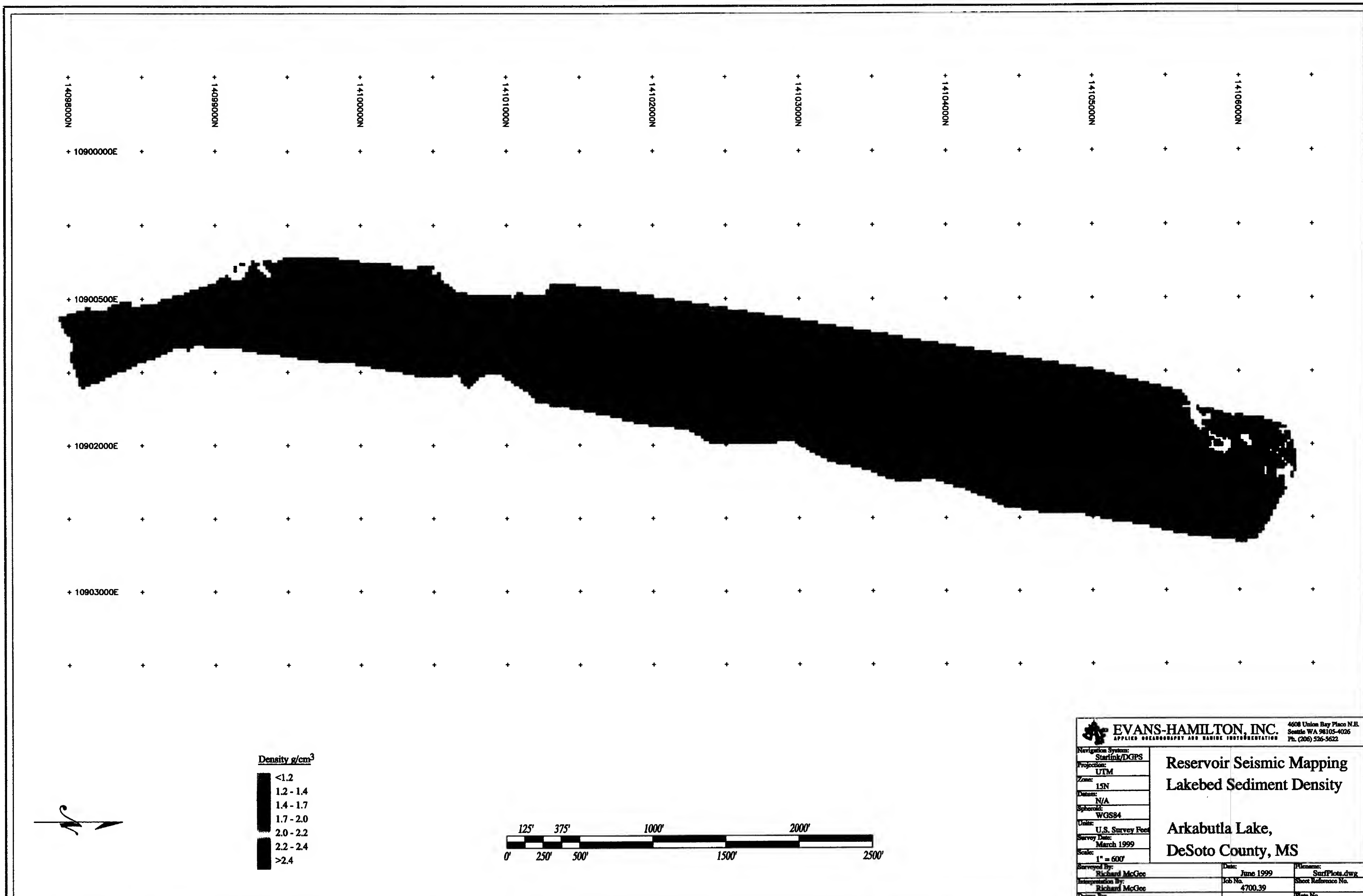


Figure 19. Surficial sediment density distribution.

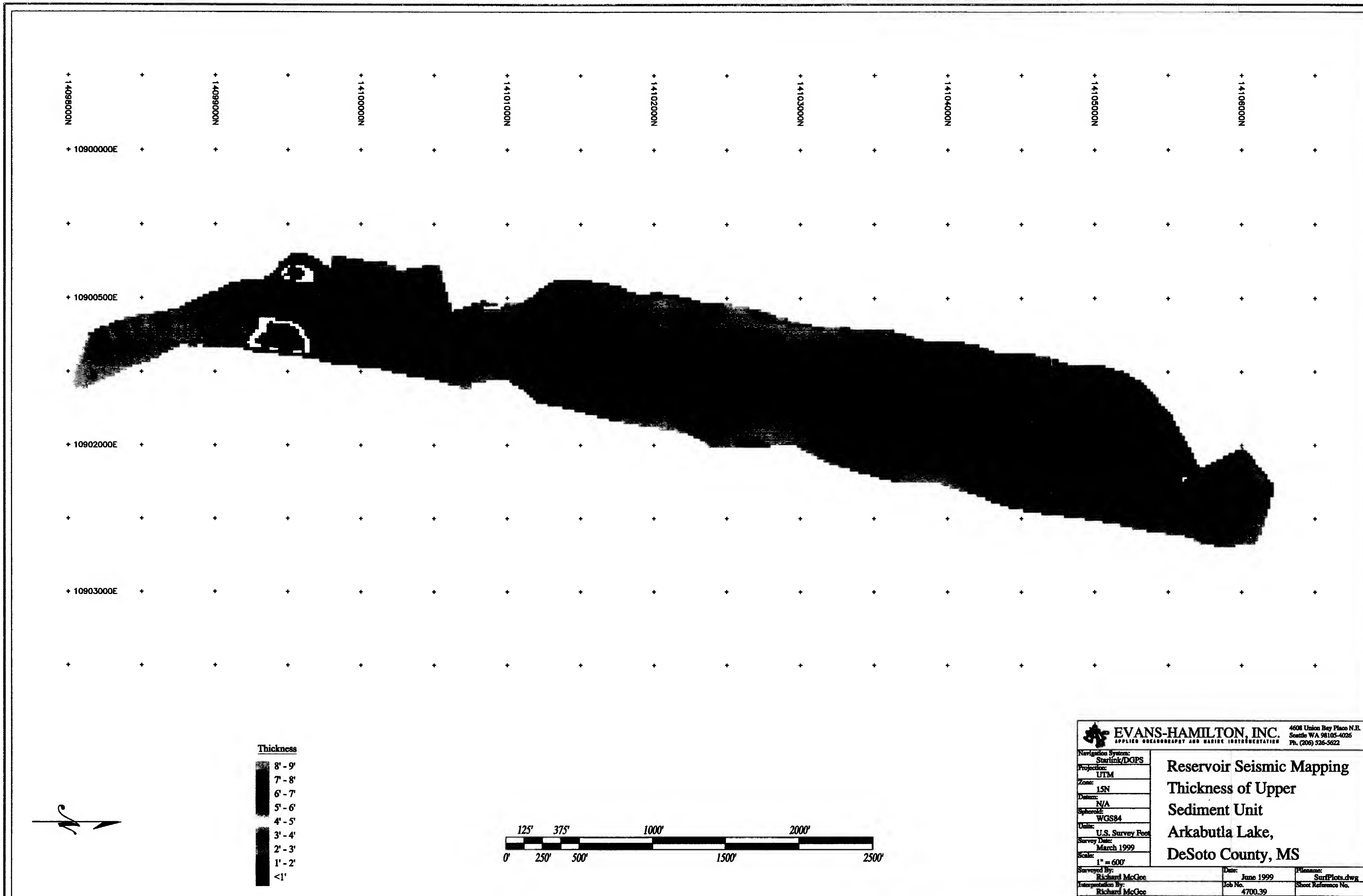
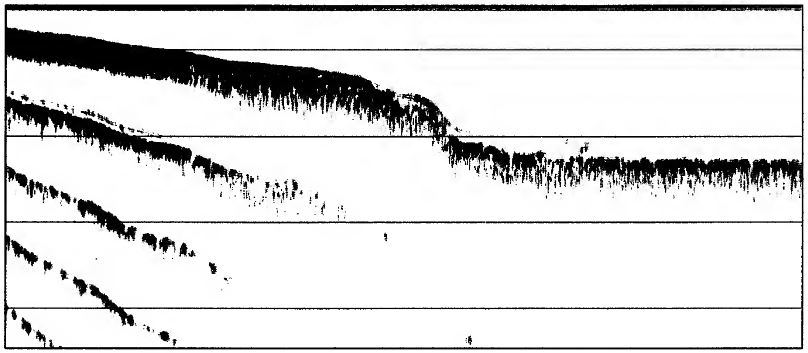
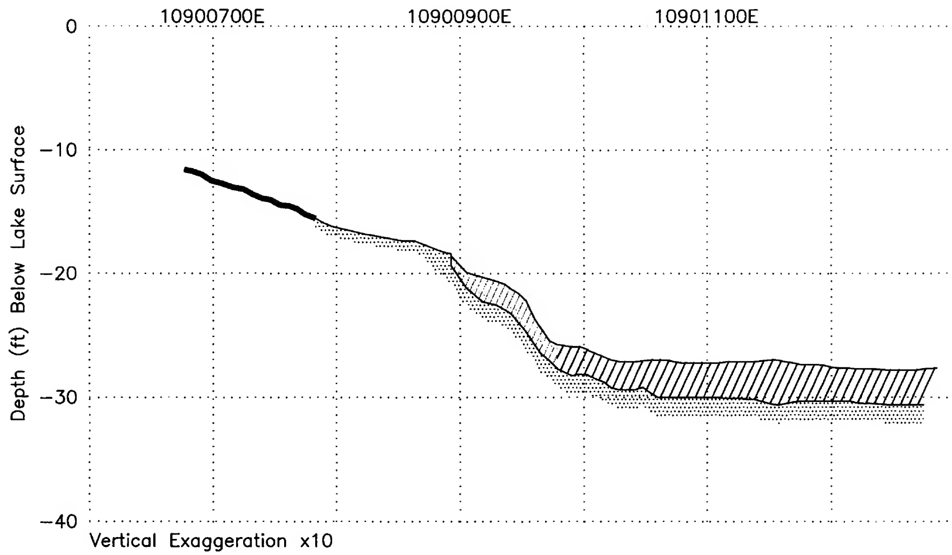
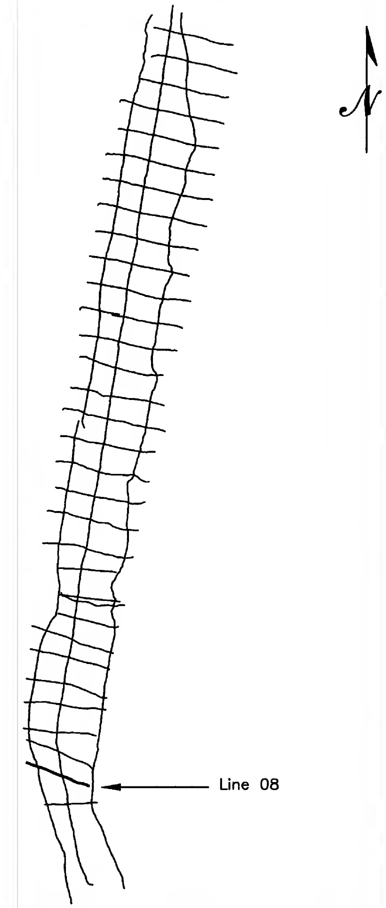


Figure 20. Thickness isopach of upper sediment unit.







LAKE ARKABUTLA SEDIMENT DESCRIPTION		
Hatch Pattern	Density g/cm^3	Basic Sediment Description
	< 1.2	Fluid Mud; Fluff
	1.2 - 1.4	Unconsolidated Mud, Saturated Clay, Silt
	1.4 - 1.7	Clay-Silt; Clay-Silt-Sand Mixtures
	1.7 - 2.0	Stiff Clayey Sand; Silty Sand; Fine Sand
	2.0 - 2.2	Dense Clays, Unsaturated Sediments, Possible Organics
	N/A	Riprap Blanket

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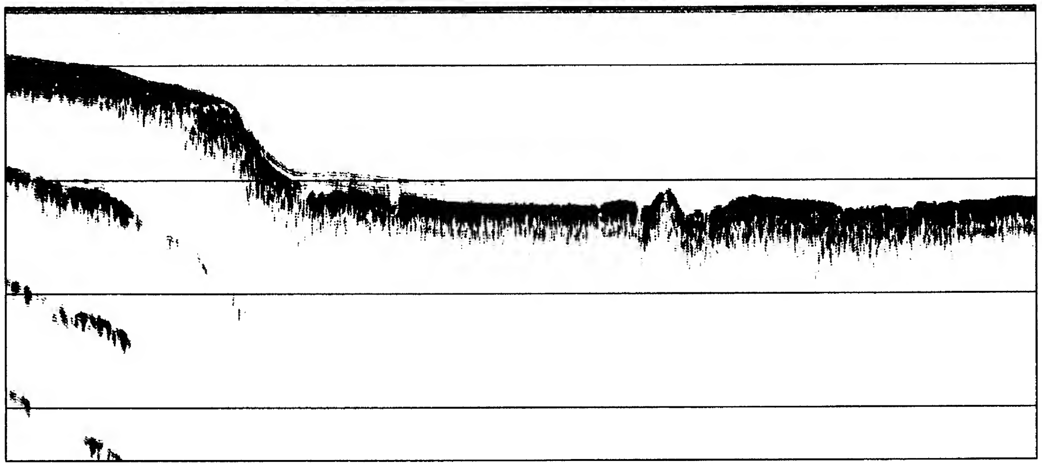
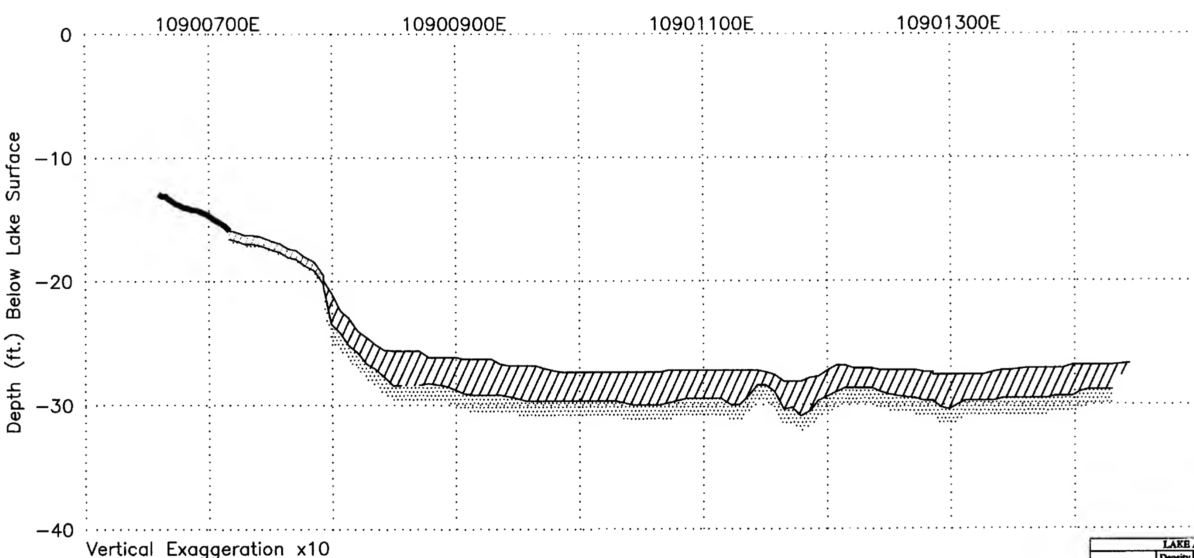
Navigation System: Starlink/DGPS
Projection: UTM
Zone: 15N
Datum: N/A
Spheroid: WGS84
Units: U.S. Survey Feet
Survey Date: March, 1999
Scale: 1" = 100'

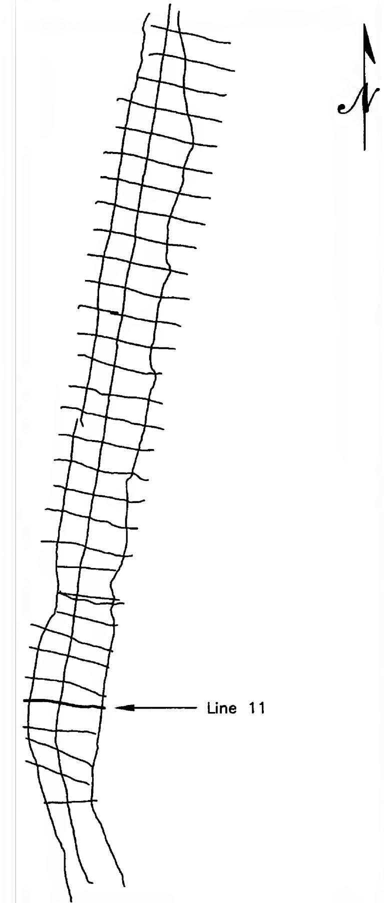
Reservoir Seismic Mapping
Arkabutla Lake,
DeSoto County, MS
3.5 kHz Profiles
Line 08

Surveyed By: Richard McGee	Date: June, 1998	Filename: SBP08.dwg
Interpretation By: Richard McGee	Job No. 4700.39	Sheet Reference No.
Drawn By: Kevin Redman		Plate No.
Checked By: Richard McGee		Sheet No.

Figure 21. Sediment profile, Line 08.







LAKE ARKABUTLA SEDIMENT DESCRIPTION		
Hatch Pattern	Density g/cm^3	Basic Sediment Description
	< 1.2	Fluid Mud; Fluff
	1.2 - 1.4	Unconsolidated Mud, Saturated Clay, Silt
	1.4 - 1.7	Clay-Silt; Clay-Silt-Sand Mixtures
	1.7 - 2.0	Stiff Clayey Sand; Silty Sand; Fine Sand
	2.0 - 2.2	Dense Clays, Unsaturated Sediments, Possible Organics
	N/A	Riprap Blanket

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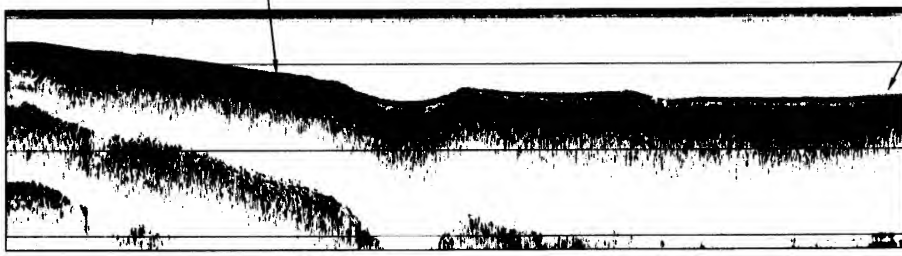
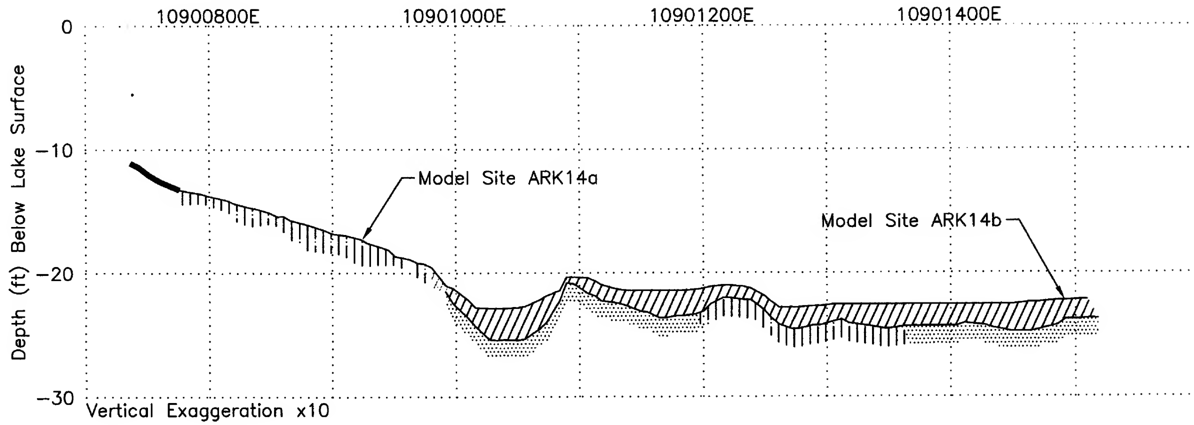
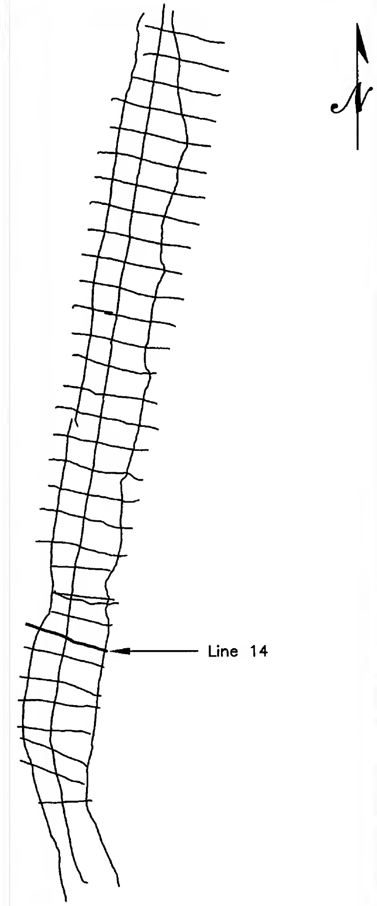
Navigation System: Starlink/DGPS	Reservoir Seismic Mapping
Projection: UTM	Arkabutla Lake,
Zone: 15N	DeSoto County, MS
Datum: N/A	3.5 kHz Profiles
Spheroid: WGS84	Line 11
Units: U.S. Survey Feet	
Survey Date: March, 1999	
Scale: 1" = 100'	

Surveyed By: Richard McGee	Date: June, 1998	Filename: SBP11.dwg
Interpretation By: Richard McGee	Job No. 4700.39	Sheet Reference No.
Drawn By: Kevin Redman		Plate No.
Checked By: Richard McGee		Sheet No.

Figure 22. Sediment profile, Line 11.







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	1.7 - 2.0	Stiff Clayey Sand; Silty Sand; Fine Sand
	2.0 - 2.2	Dense Clays, Unsaturated Sediments, Possible Organics
	N/A	Riprap Blanket

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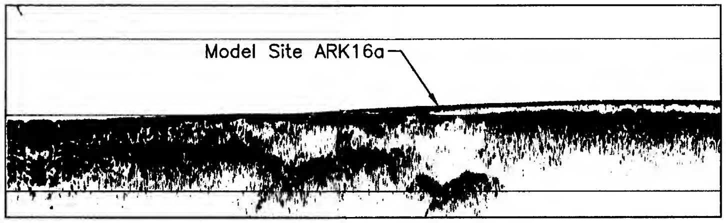
Seattle WA 98105-4026
Ph. (206) 526-5622

Navigation System: Starlink/DGPS	Reservoir Seismic Mapping
Projection: UTM	Arkabutla Lake,
Zone: 15N	DeSoto County, MS
Datum: N/A	3.5 kHz Profiles
Spheroid: WGS84	Line 14
Units: U.S. Survey Feet	
Survey Date: March, 1999	
Scale: 1" = 100'	

Surveyed By: Richard McGee	Date: June, 1998	Filename: SBP14.dwg
Interpretation By: Richard McGee	Job No. 4700.39	Sheet Reference No.
Drawn By: Kevin Redman		Plate No.
Checked By: Richard McGee		Sheet No.

Figure 23. Sediment profile, Line 14.



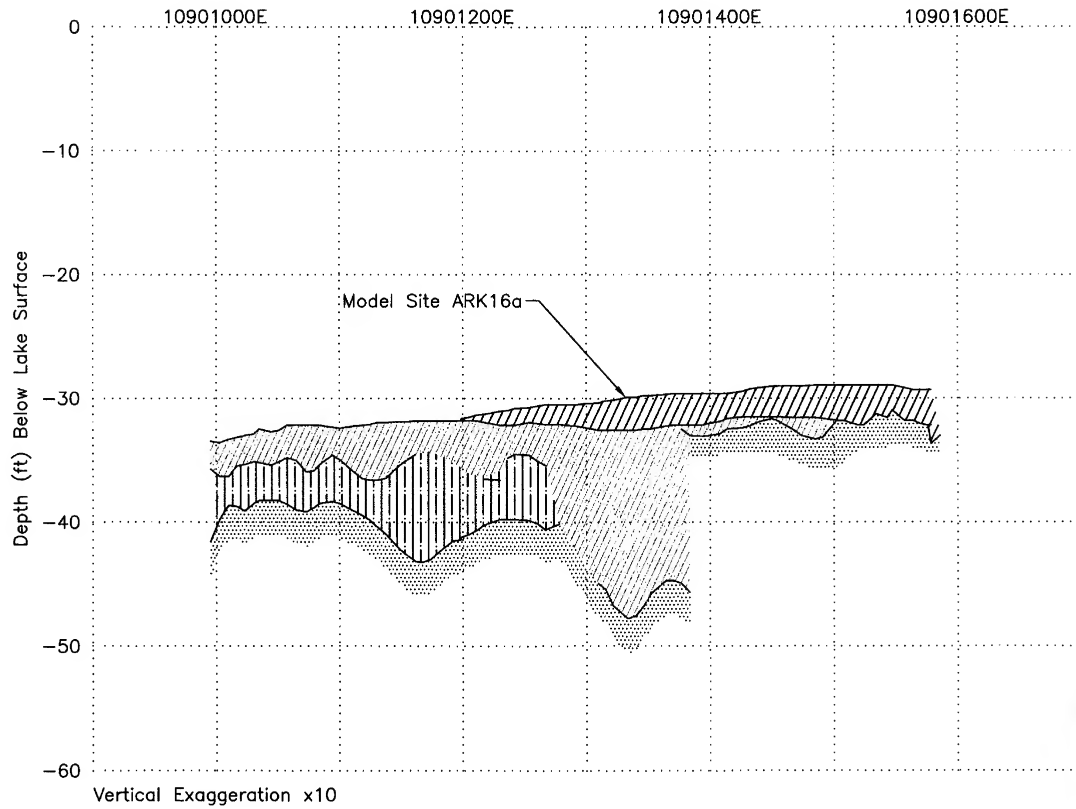
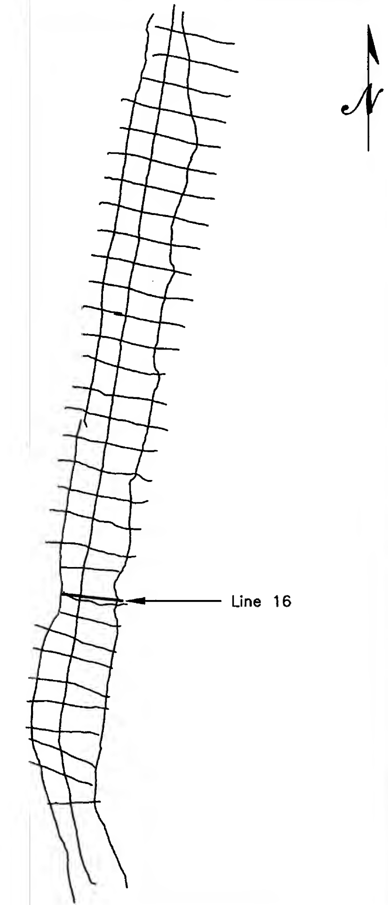


Figure 24. Sediment profile, Line 16.

LAKE ARKABUTLA SEDIMENT DESCRIPTION		
Hatch Pattern	Density g/cm^3	Basic Sediment Description
	< 1.2	Fluid Mud; Fluff
	1.2 - 1.4	Unconsolidated Mud, Saturated Clay, Silt
	1.4 - 1.7	Clay-Silt; Clay-Silt-Sand Mixtures
	1.7 - 2.0	Stiff Clayey Sand; Silty Sand; Fine Sand
	2.0 - 2.2	Dense Clays, Unsaturated Sediments, Possible Organics
	N/A	Riprap Blanket



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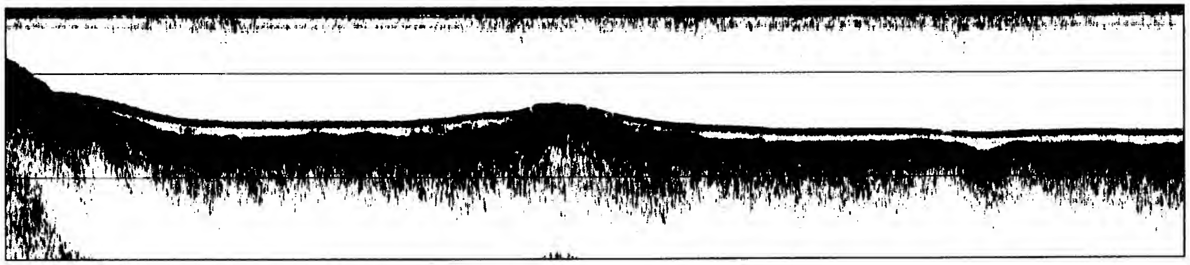
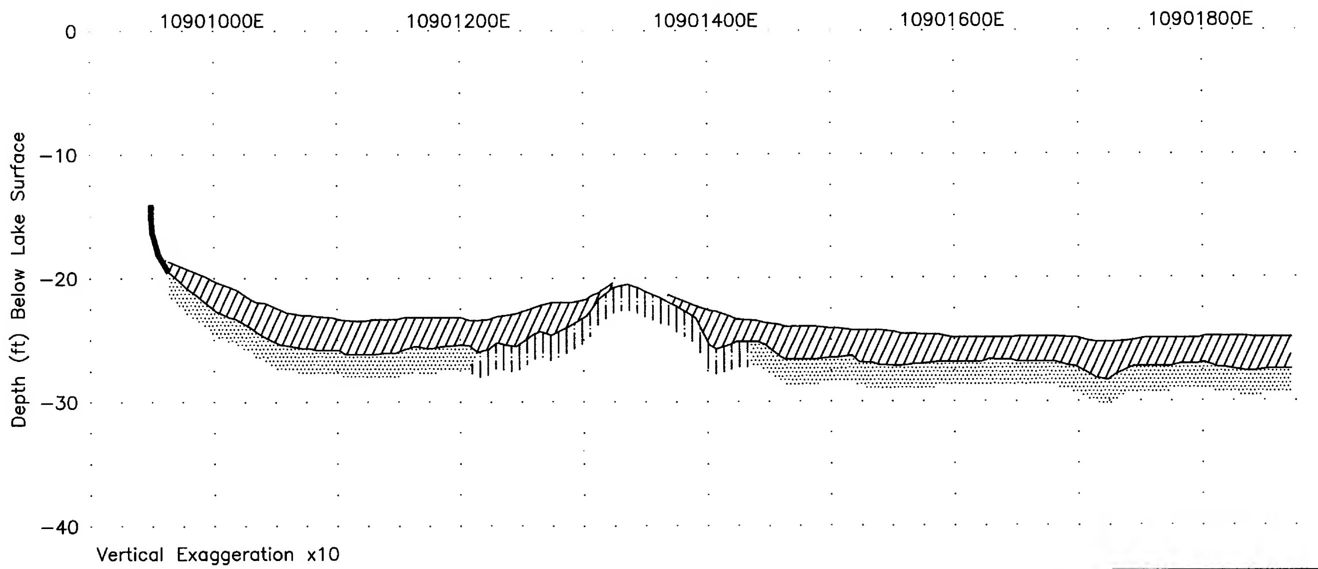
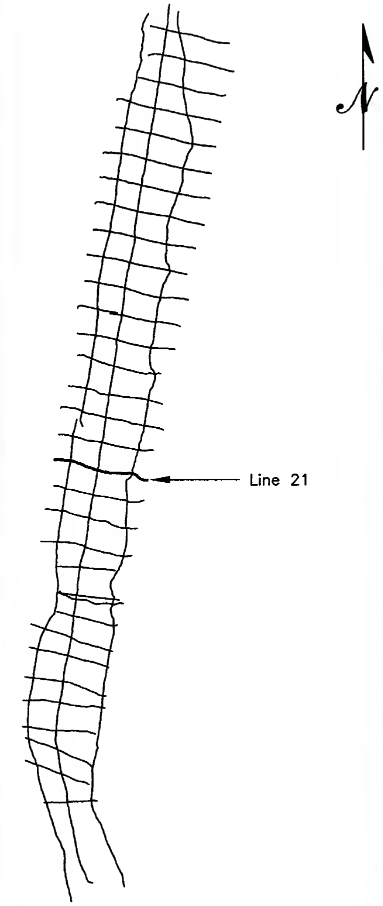
Reservoir Seismic Mapping
Arkabutla Lake,
DeSoto County, MS
3.5 kHz Profiles
Line 16

Navigation System: Starlink/DGPS
Projection: UTM
Zone: 15N
Datum: N/A
Spheroid: WGS84
Units: U.S. Survey Feet
Survey Date: March, 1999
Scale: 1" = 100'
Surveyed By: Richard McGee
Interpretation By: Richard McGee
Drawn By: Kevin Redman
Checked By: Richard McGee
Date: June, 1999
Job No. 4700.39
Filename: SBP16.dwg
Sheet Reference No.
Plate No.
Sheet No.







LAKE ARKABUTLA SEDIMENT DESCRIPTION		
Hatch Pattern	Density g/cm³	Basic Sediment Description
	< 1.2	Fluid Mud; Fluff
	1.2 - 1.4	Unconsolidated Mud, Saturated Clay, Silt
	1.4 - 1.7	Clay-Silt; Clay-Silt-Sand Mixtures
	1.7 - 2.0	Stiff Clayey Sand; Silty Sand; Fine Sand
	2.0 - 2.2	Dense Clays, Unsaturated Sediments, Possible Organics
	N/A	Riprap Blanket

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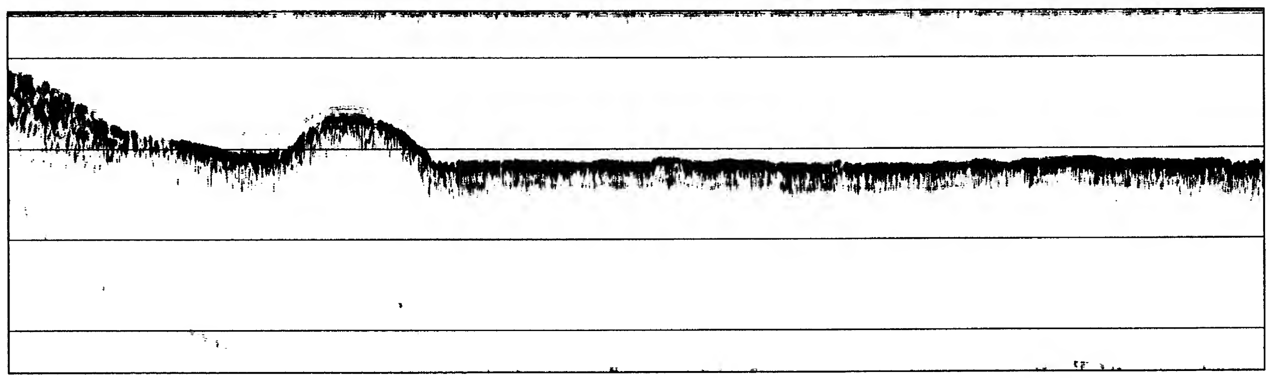
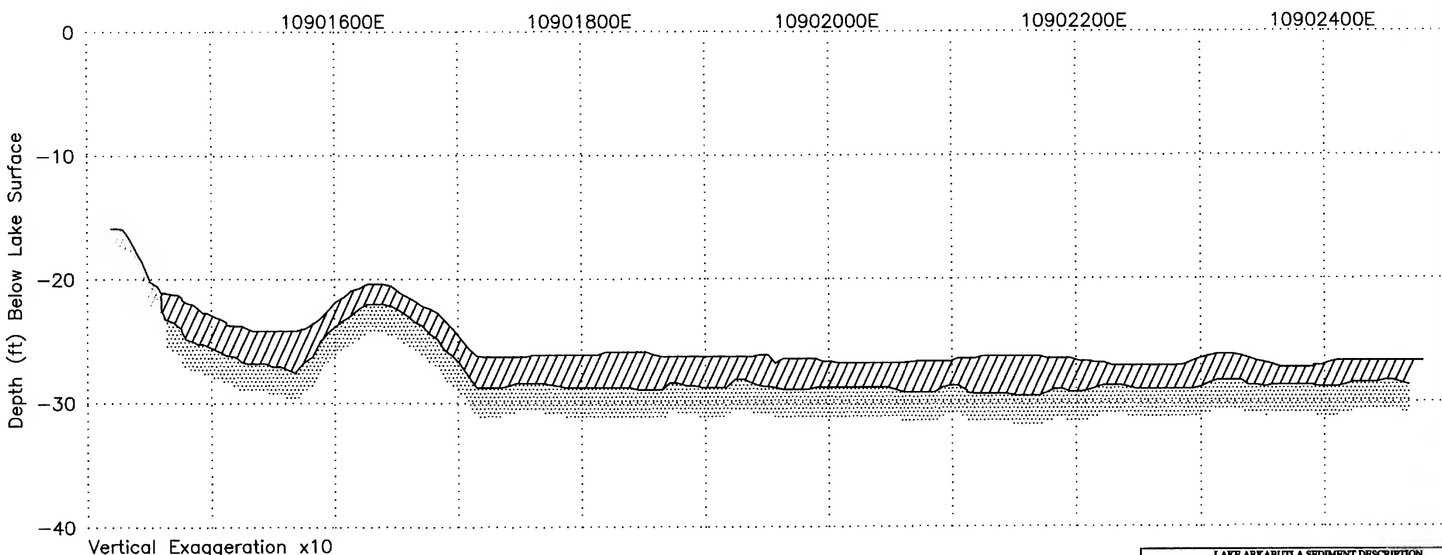
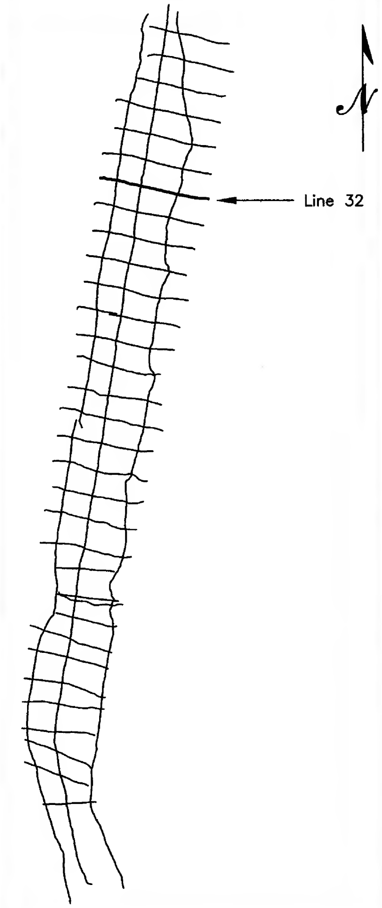
Navigation System: Starlink/DGPS	Reservoir Seismic Mapping
Projection: UTM	Arkabutla Lake,
Zone: 15N	DeSoto County, MS
Datum: N/A	3.5 kHz Profile
Spheroid: WGS84	Line 21
Units: U.S. Survey Feet	
Survey Date: March, 1999	
Scale: 1" = 100'	

Surveyed By: Richard McGee	Date: June, 1999	Filename: SBP21.dwg
Interpretation By: Richard McGee	Job No. 4700.39	Sheet Reference No.
Drawn By: Kevin Redman		Plate No.
Checked By: Richard McGee		Sheet No.

Figure 25. Sediment profile, Line 21.







LAKE ARKABUTLA SEDIMENT DESCRIPTION		
Hatch Pattern	Density g/cm^3	Basic Sediment Description
	< 1.2	Fluid Mud; Fluff
	1.2 - 1.4	Unconsolidated Mud, Saturated Clay, Silt
	1.4 - 1.7	Clay-Silt; Clay-Silt-Sand Mixtures
	1.7 - 2.0	Stiff Clayey Sand; Silty Sand; Fine Sand
	2.0 - 2.2	Dense Clays, Unsaturated Sediments, Possible Organics
	N/A	Riprap Blanket

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Seattle WA 98105-4026
Ph. (206) 526-5622

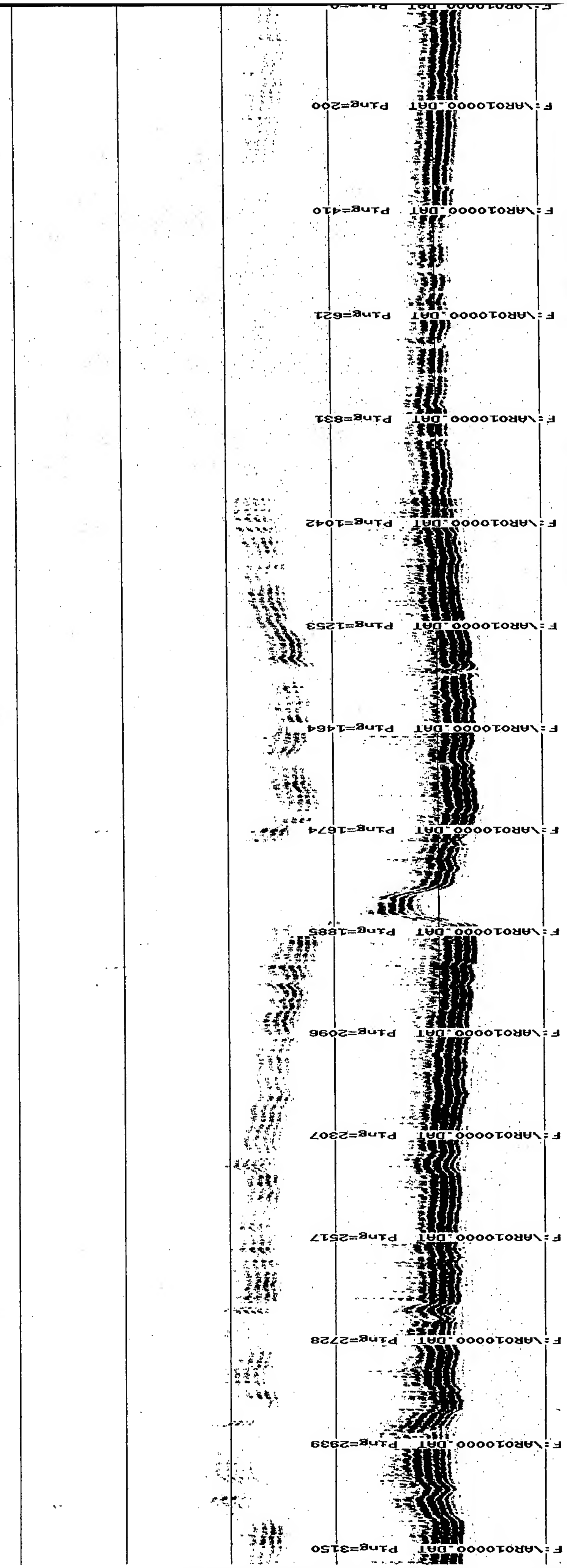
Navigation System: Starlink/DGPS
Projection: UTM
Zone: 15N
Datum: WGS84
Spheroid:
Units: U.S. Survey Feet
Survey Date: March, 1999
Scale: 1" = 100'

Reservoir Seismic Mapping
Arkabutla Lake,
DeSoto County, MS
3.5 kHz Profiles
Line 32

Surveyed By: Richard McGee	Date: June, 1998	Filename: SBP32.dwg
Interpretation By: Richard McGee	Job No. 4700.39	Sheet Reference No.
Drawn By: Kevin Redman		Plate No.
Checked By: Richard McGee		Sheet No.

Figure 26. Sediment profile, Line 32.

Appendix A
1-kHz Subbottom Profile Data



F:\AR010000.DAT Ping=200
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F:\AR010000.DAT Ping=621
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F:\AR010000.DAT Ping=1042
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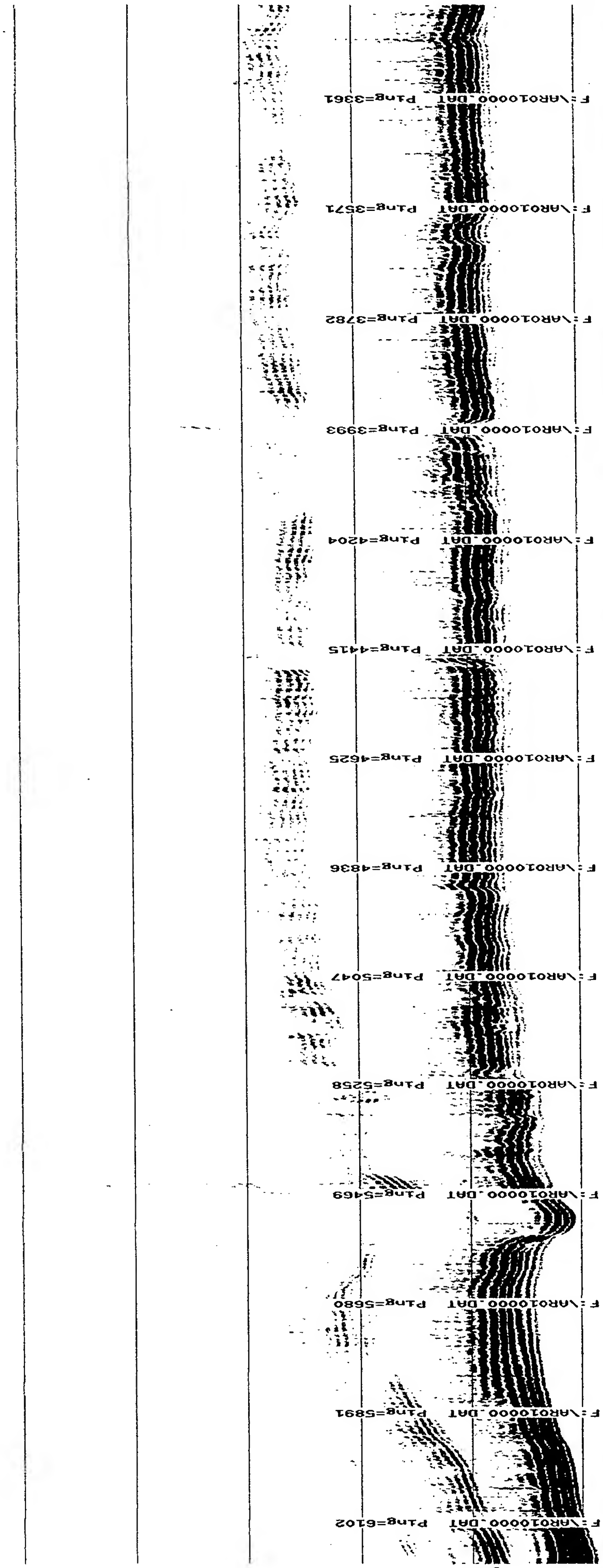
F:\AR010000.DAT Ping=1885
F:\AR010000.DAT Ping=2096
F:\AR010000.DAT Ping=2307
F:\AR010000.DAT Ping=2517
F:\AR010000.DAT Ping=2728
F:\AR010000.DAT Ping=2939
F:\AR010000.DAT Ping=3150

A2


F:\AR010000.DAT Ping=3361
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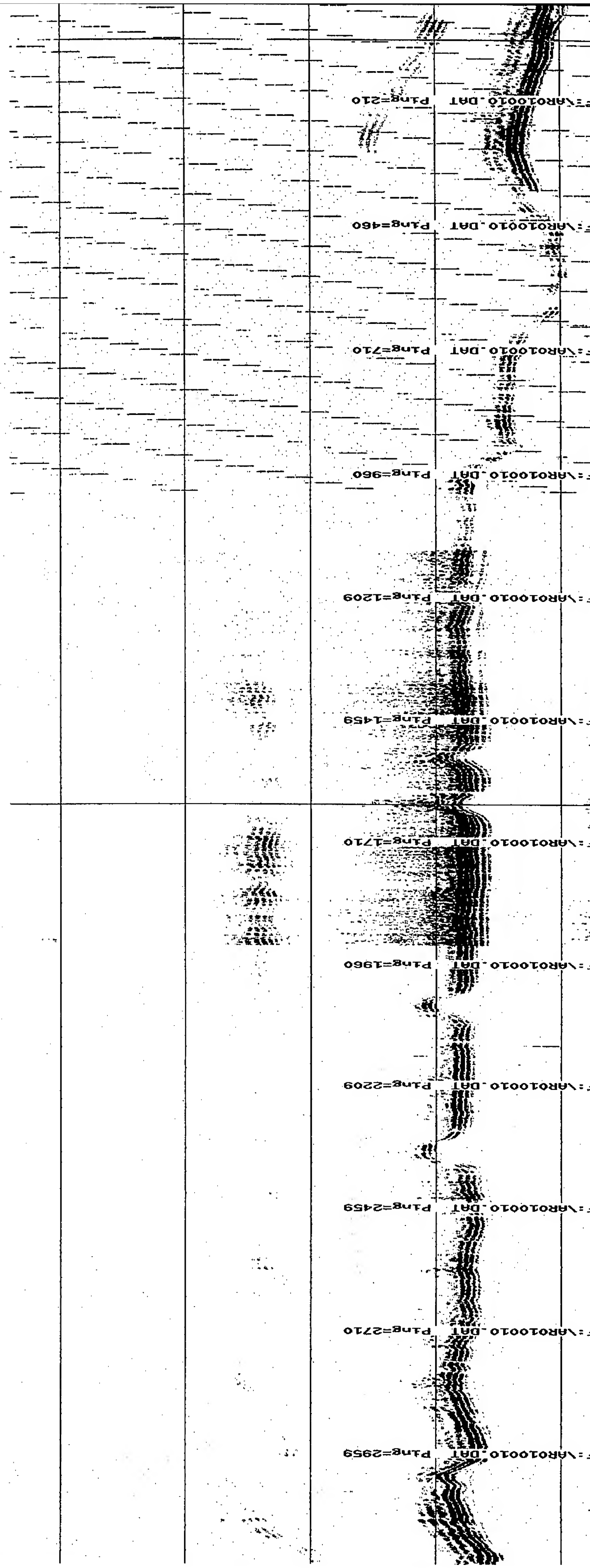
F:\AR010000.DAT Ping=4836
F:\AR010000.DAT Ping=5047
F:\AR010000.DAT Ping=5258
F:\AR010000.DAT Ping=5469
F:\AR010000.DAT Ping=5680
F:\AR010000.DAT Ping=5891
F:\AR010000.DAT Ping=6102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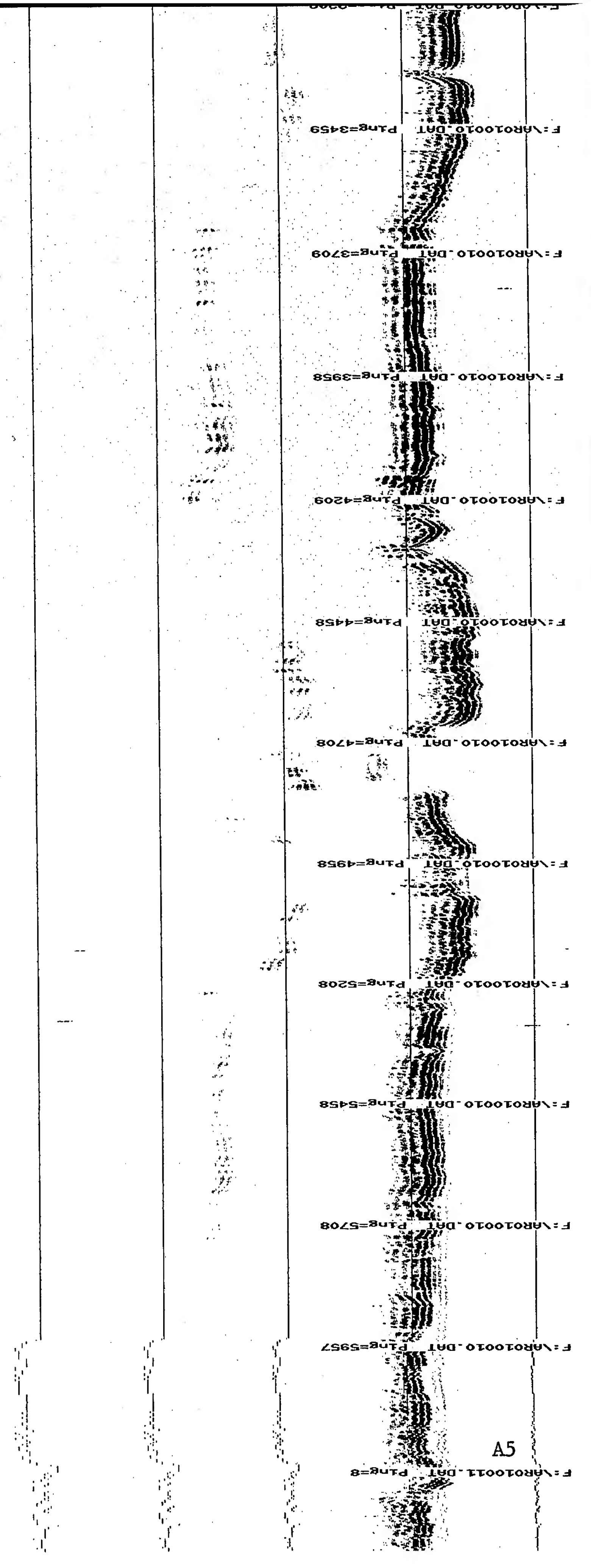
F:\AR010010.DAT Ping=460
F:\AR010010.DAT Ping=710
F:\AR010010.DAT Ping=960
F:\AR010010.DAT Ping=1209
F:\AR010010.DAT Ping=1459
F:\AR010010.DAT Ping=1710
F:\AR010010.DAT Ping=1960
F:\AR010010.DAT Ping=2209
F:\AR010010.DAT Ping=2459
F:\AR010010.DAT Ping=2710
F:\AR010010.DAT Ping=2959

A4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F:\AR010010.DAT Ping=4708
F:\AR010010.DAT Ping=4958
F:\AR010010.DAT Ping=5208
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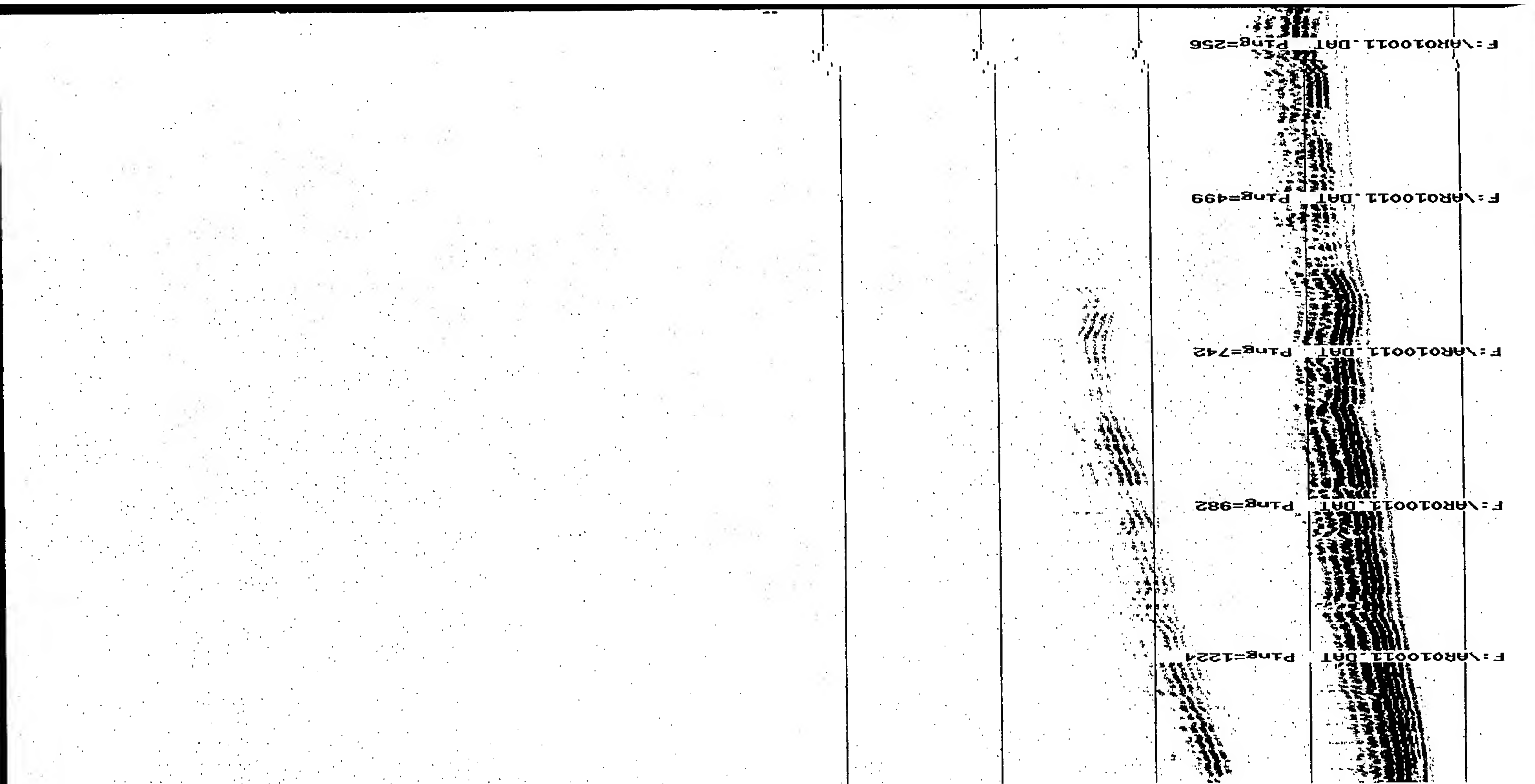
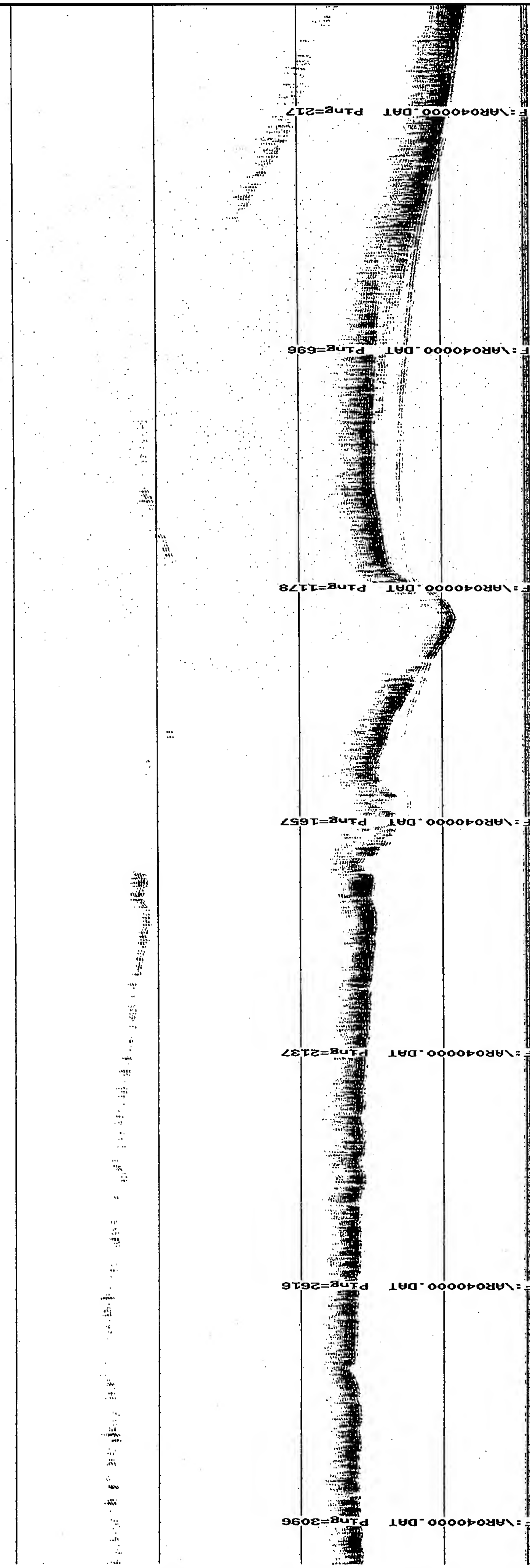
F:\AR010010.DAT Ping=5708
F:\AR010010.DAT Ping=5957
F:\AR010011.DAT Ping=8


F:\AR010011.DAT Ping=256
F:\AR010011.DAT Ping=499
F:\AR010011.DAT Ping=742
F:\AR010011.DAT Ping=982
F:\AR010011.DAT Ping=1224

Appendix B
4-kHz Subbottom Profile Records


F:\AR040000.DAT Ping=217
F:\AR040000.DAT Ping=696
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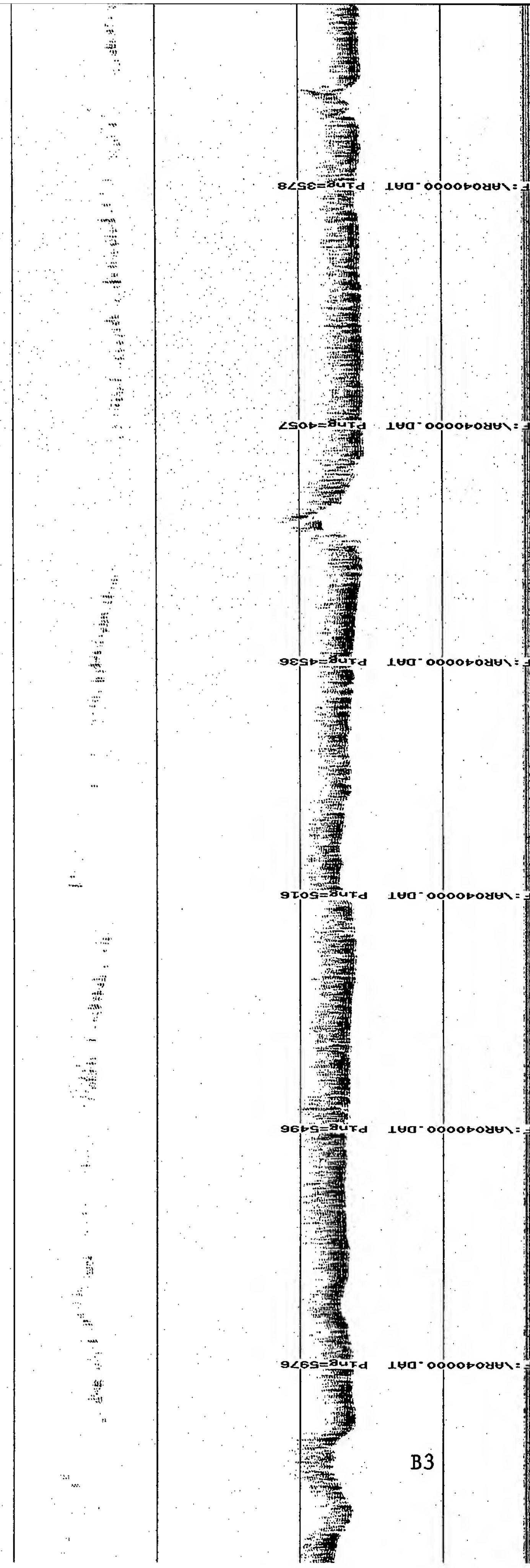
F:\AR040000.DAT Ping=2616
F:\AR040000.DAT Ping=3096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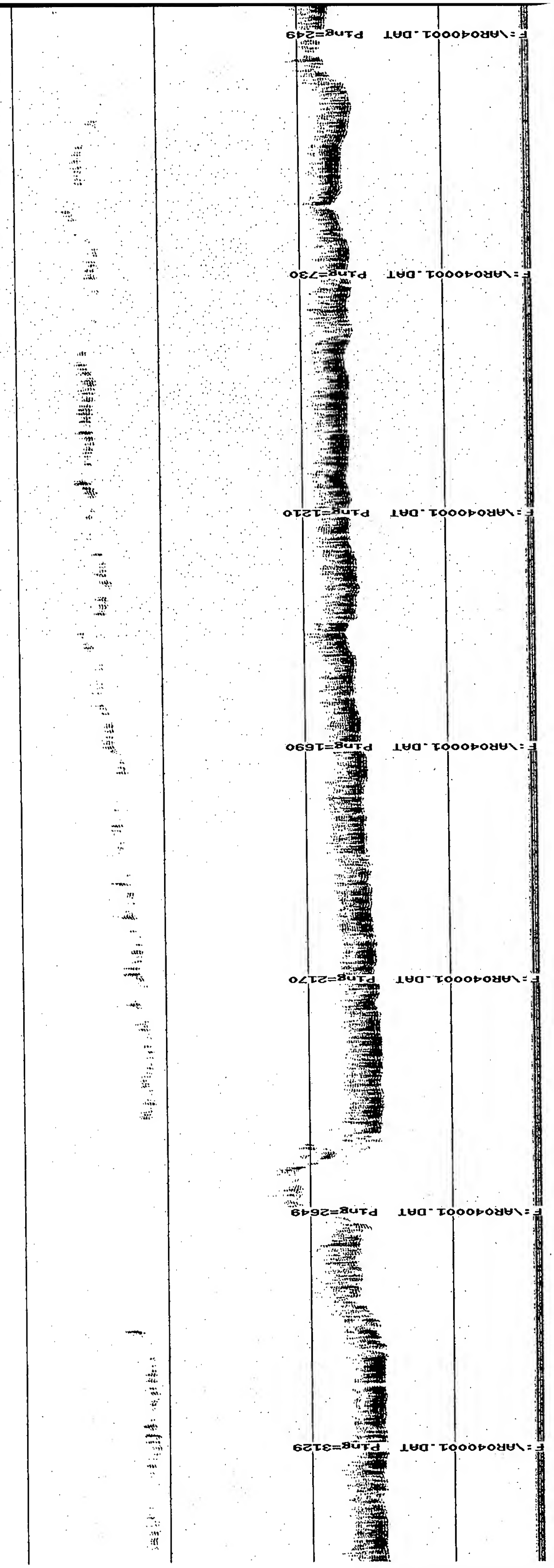
F:\AR040000.DAT Ping=5496
F:\AR040000.DAT Ping=5976

B3


F:\AR040001.DAT Ping=249
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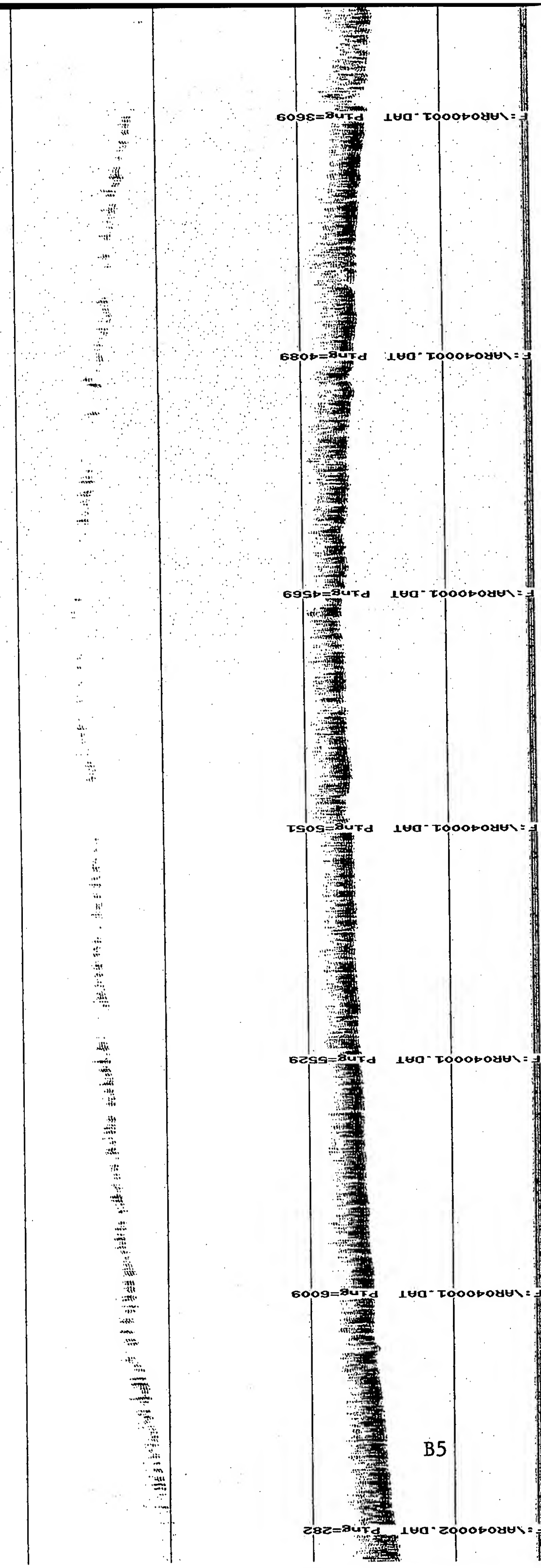
F:\AR040001.DAT Ping=1690
F:\AR040001.DAT Ping=2170
F:\AR040001.DAT Ping=2649
F:\AR040001.DAT Ping=3129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F:\AR04001.DAT Ping=4569
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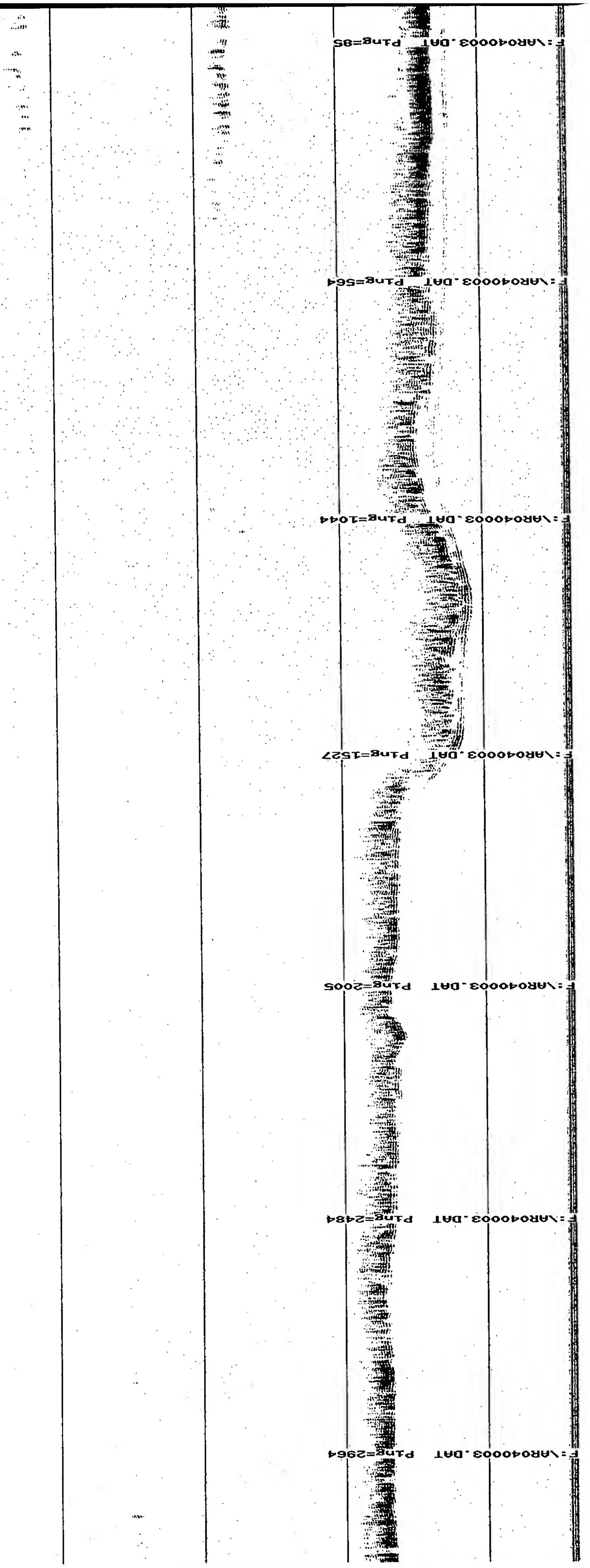
F:\AR04001.DAT Ping=6009
F:\AR04002.DAT Ping=282

B5


F:\AR040003.DAT Ping=85
F:\AR040003.DAT Ping=564
F:\AR040003.DAT Ping=1044
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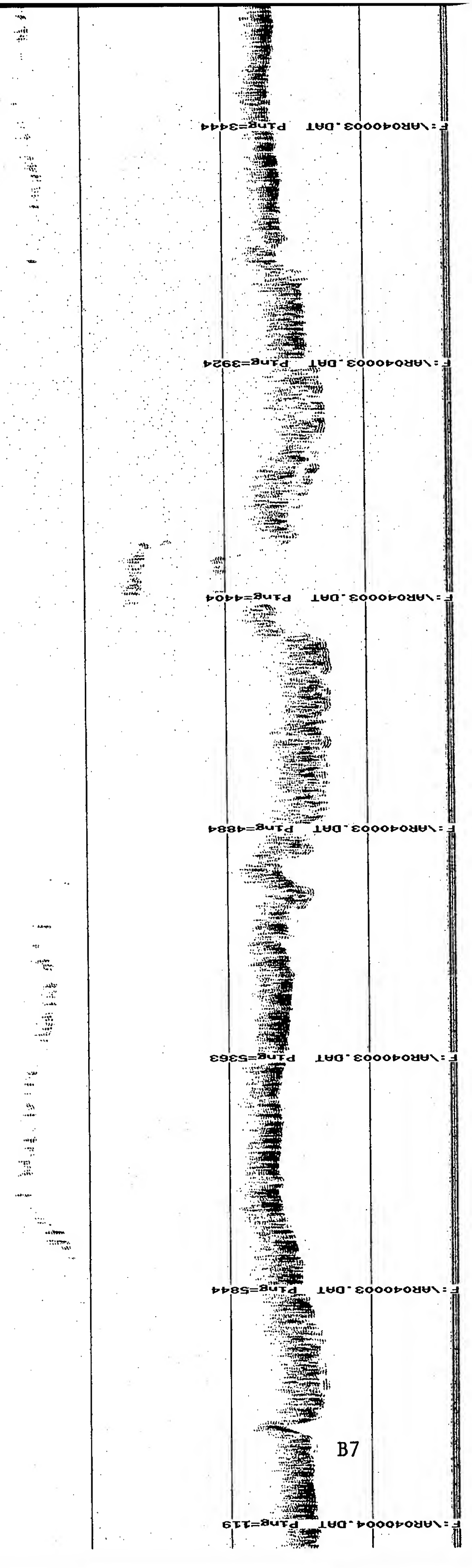
F:\AR040003.DAT Ping=2005
F:\AR040003.DAT Ping=2484
F:\AR040003.DAT Ping=2964


F:\AR040003.DAT Ping=3444
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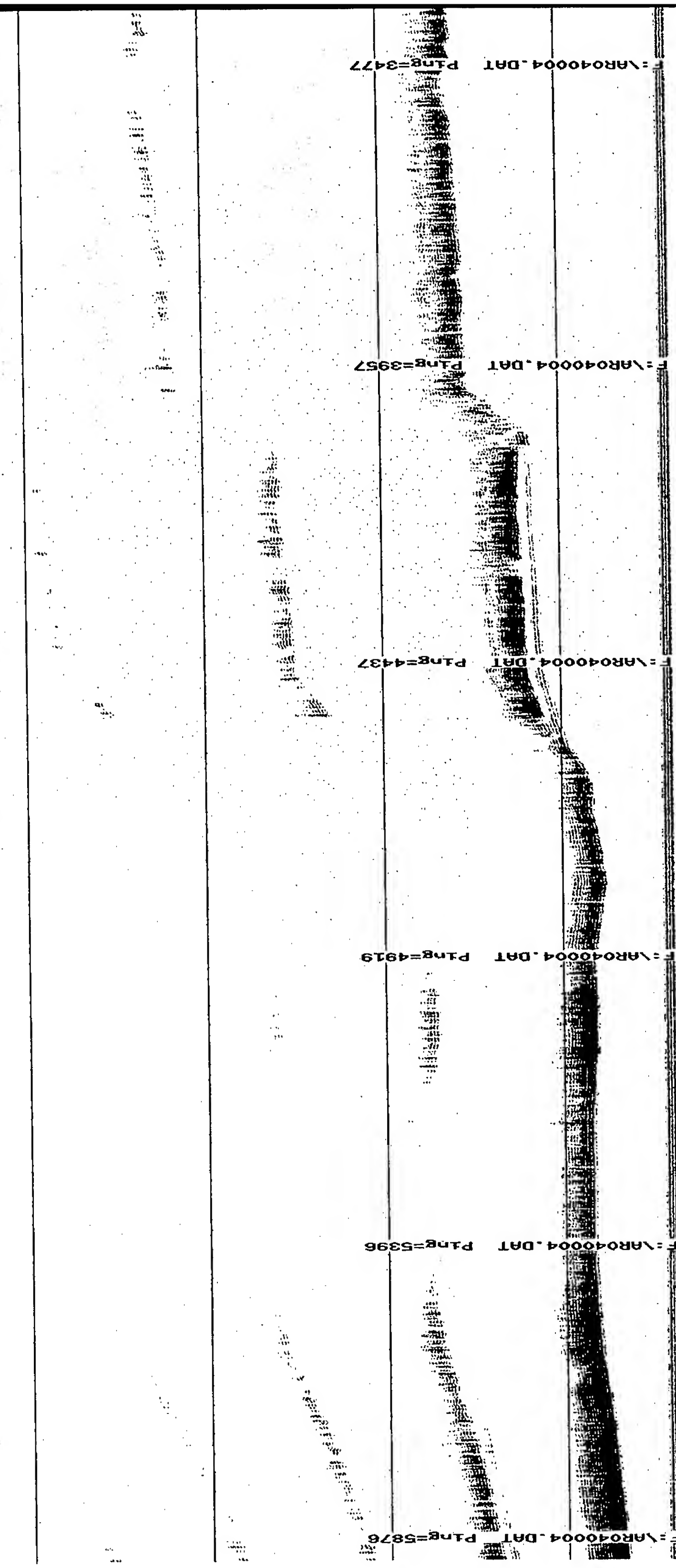
F:\AR040003.DAT Ping=4404
F:\AR040003.DAT Ping=4884
F:\AR040003.DAT Ping=5363
F:\AR040003.DAT Ping=5844
F:\AR040004.DAT Ping=119

B7


F:\AR040004.DAT Ping=3477
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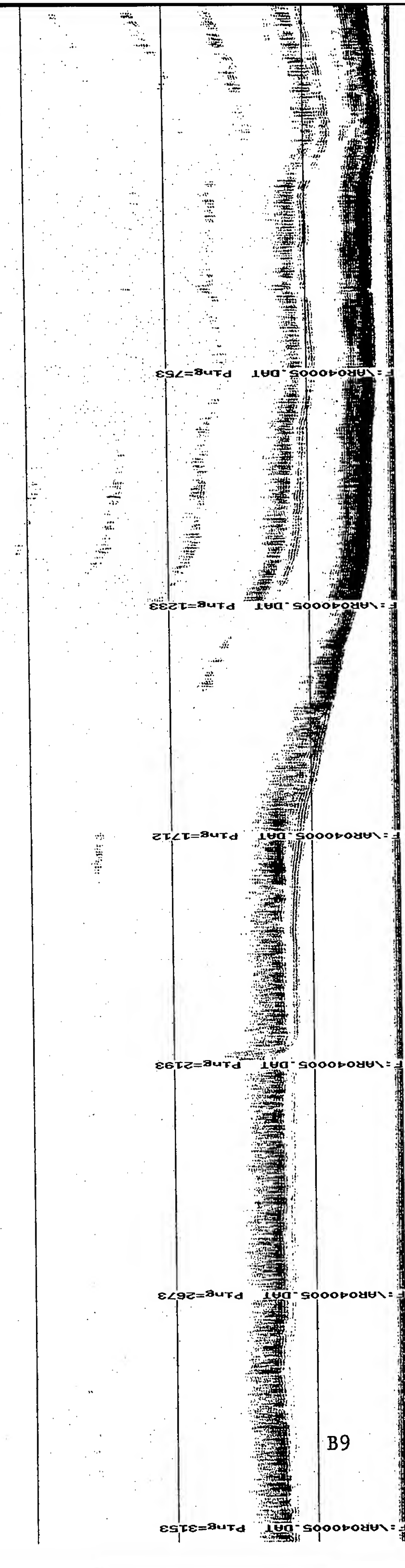

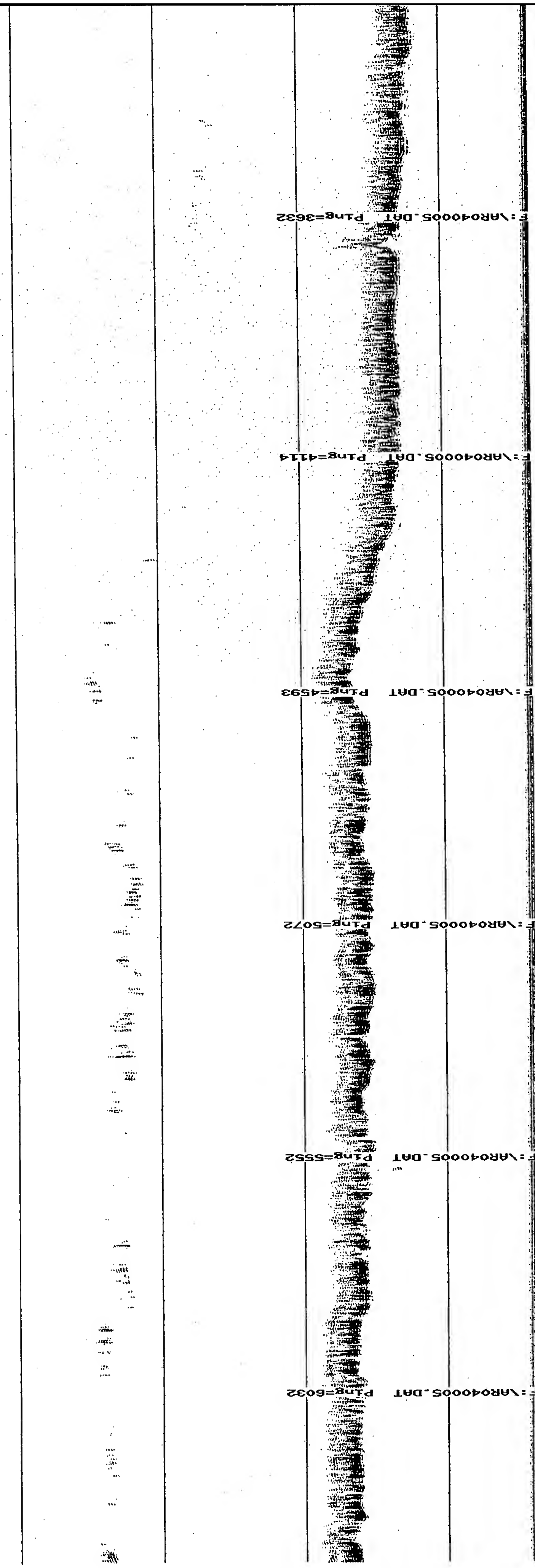

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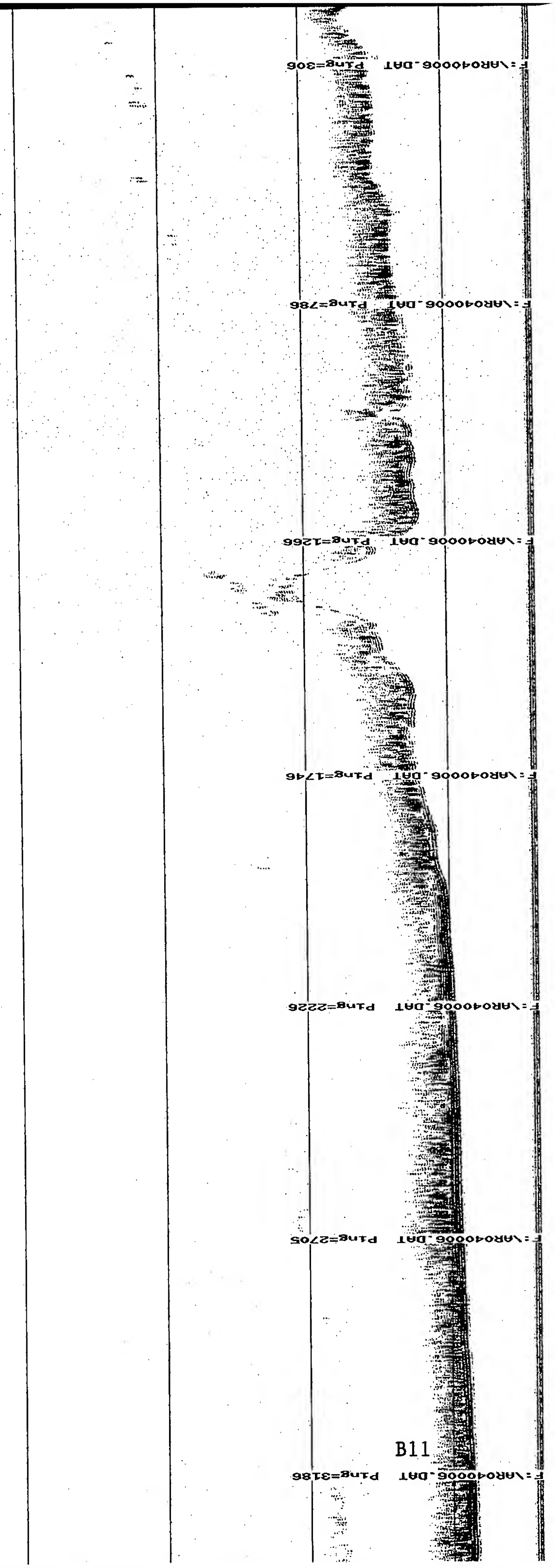
B10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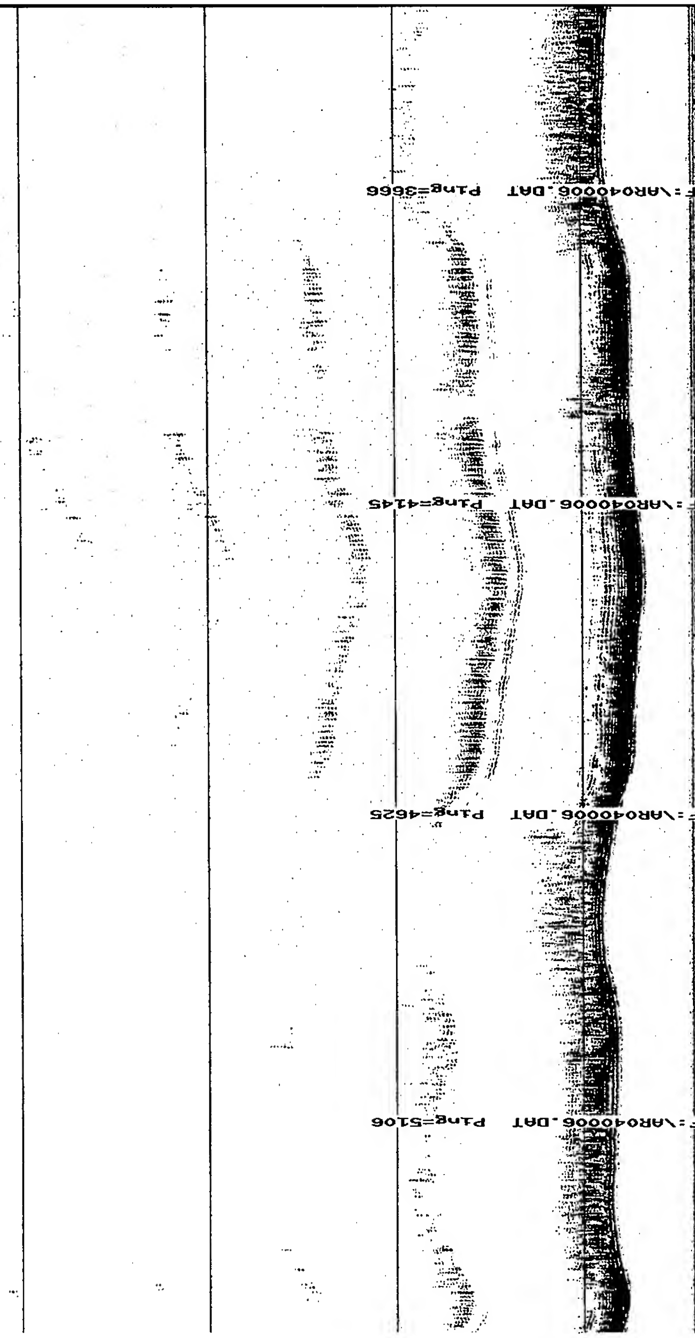
B11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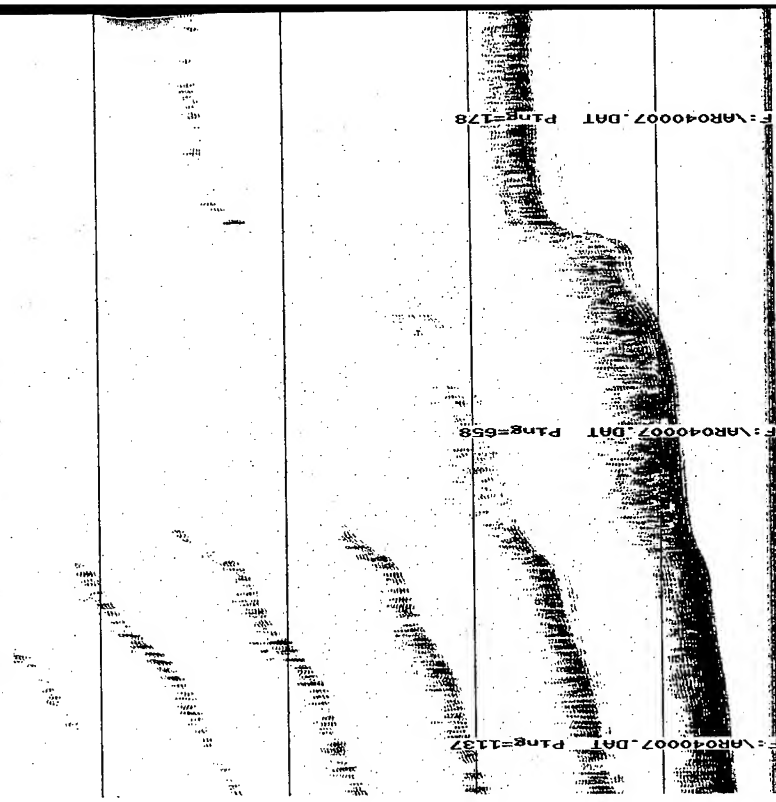
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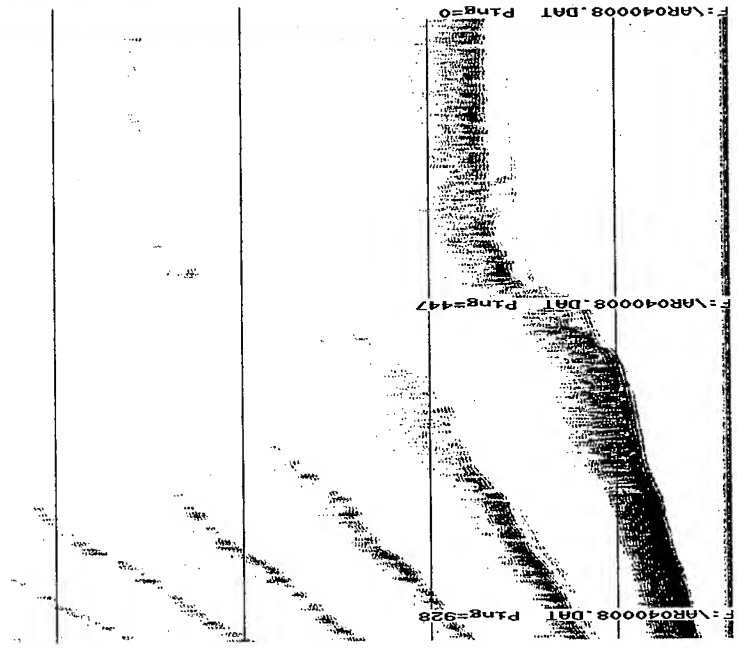
F:\AR040008.DAT Ping=0
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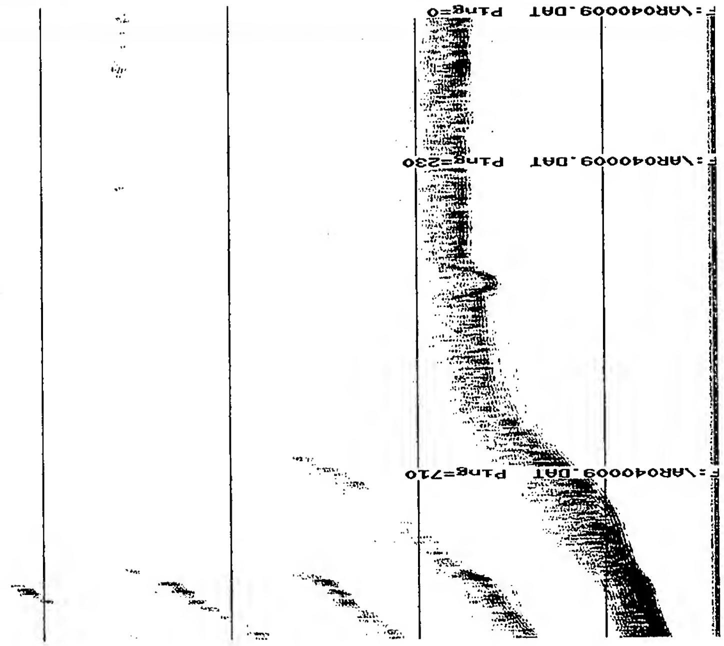
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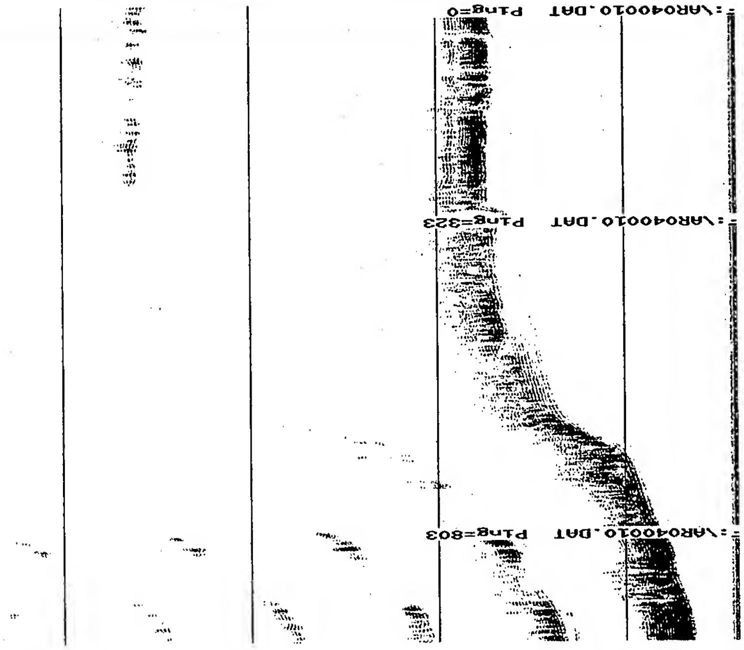
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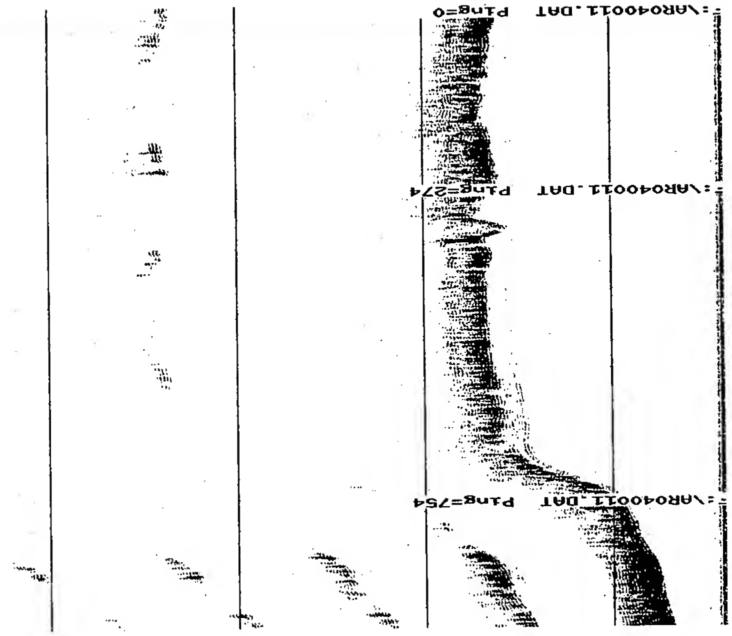
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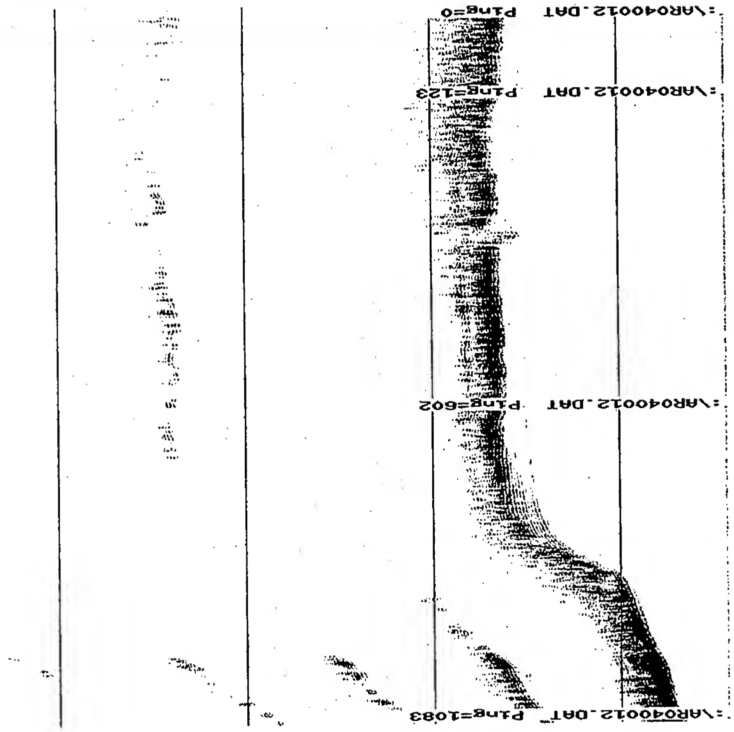
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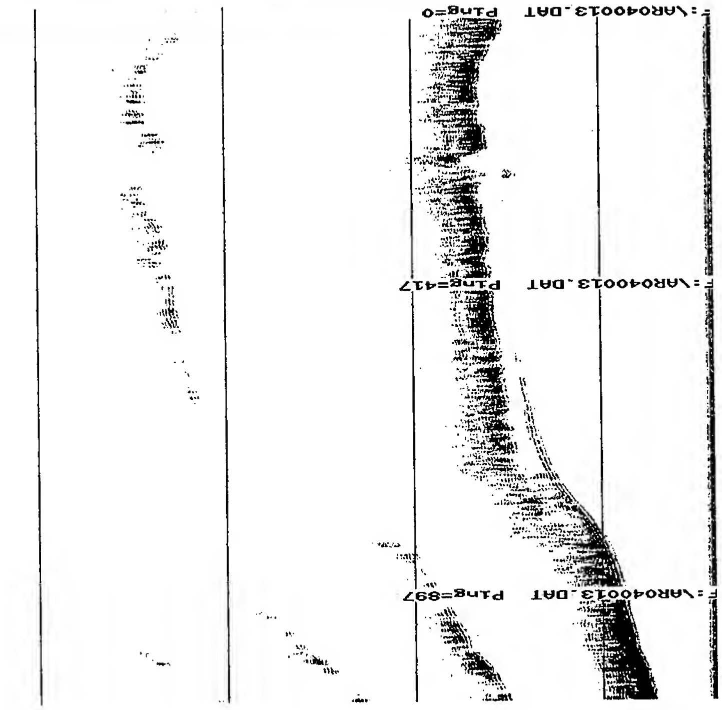
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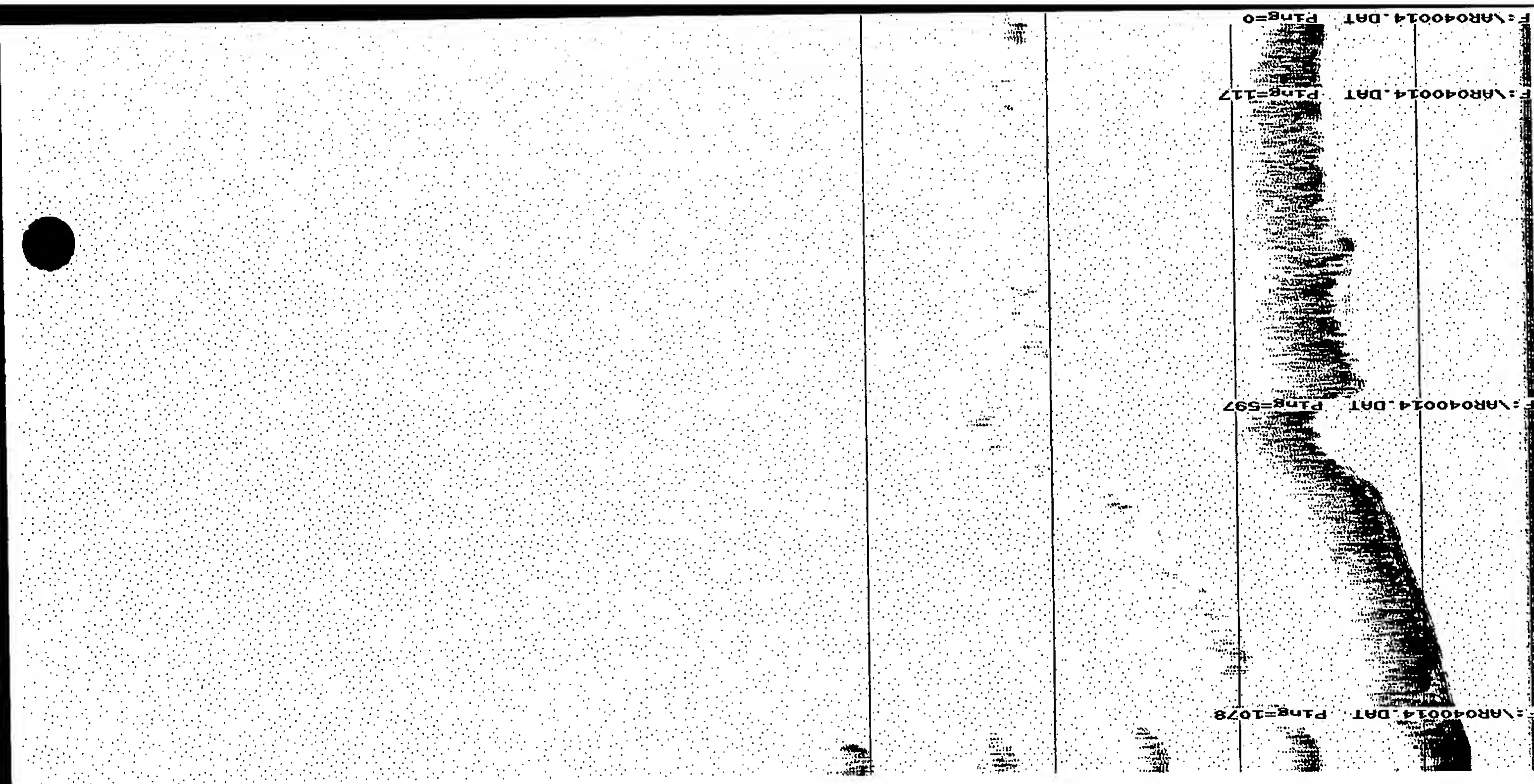
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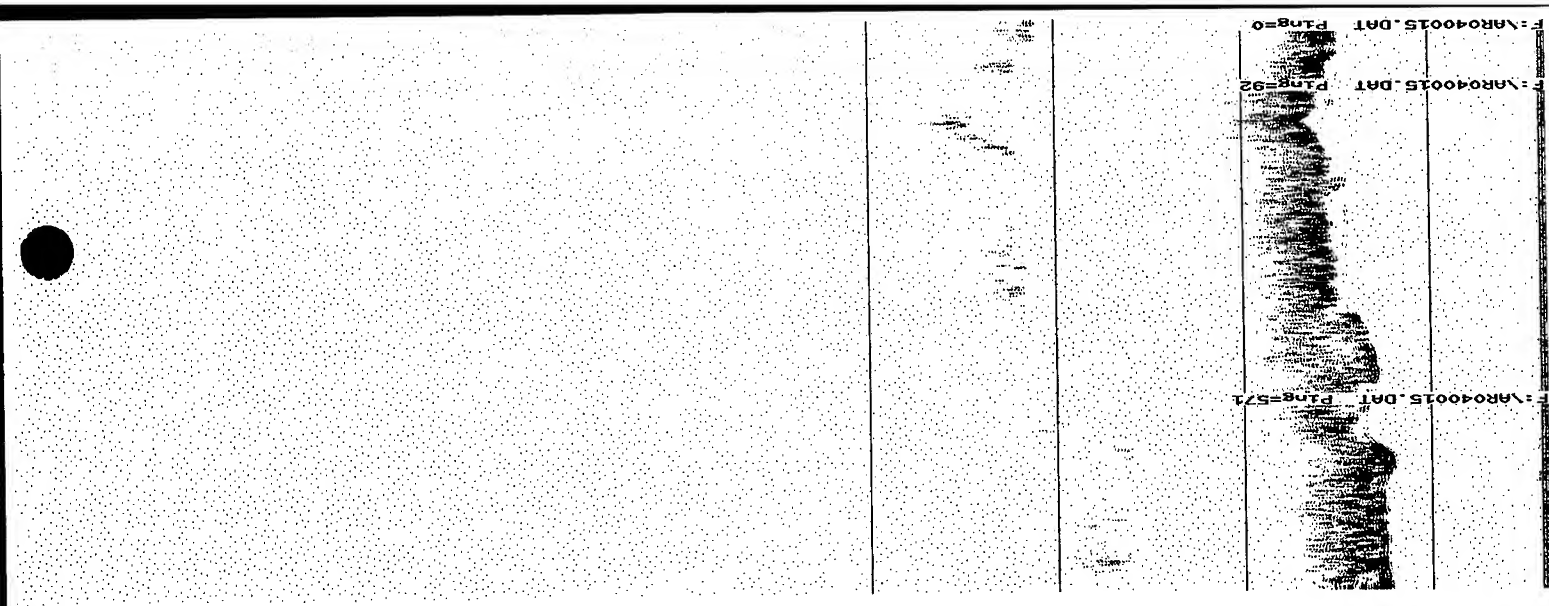
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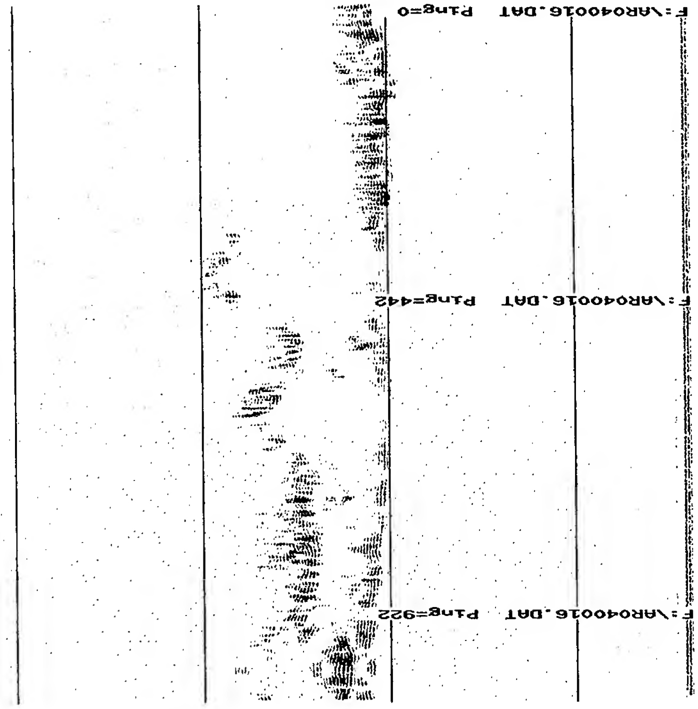
F:\AR040016.DAT Ping=0
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F:\AR040017.DAT Ping=0
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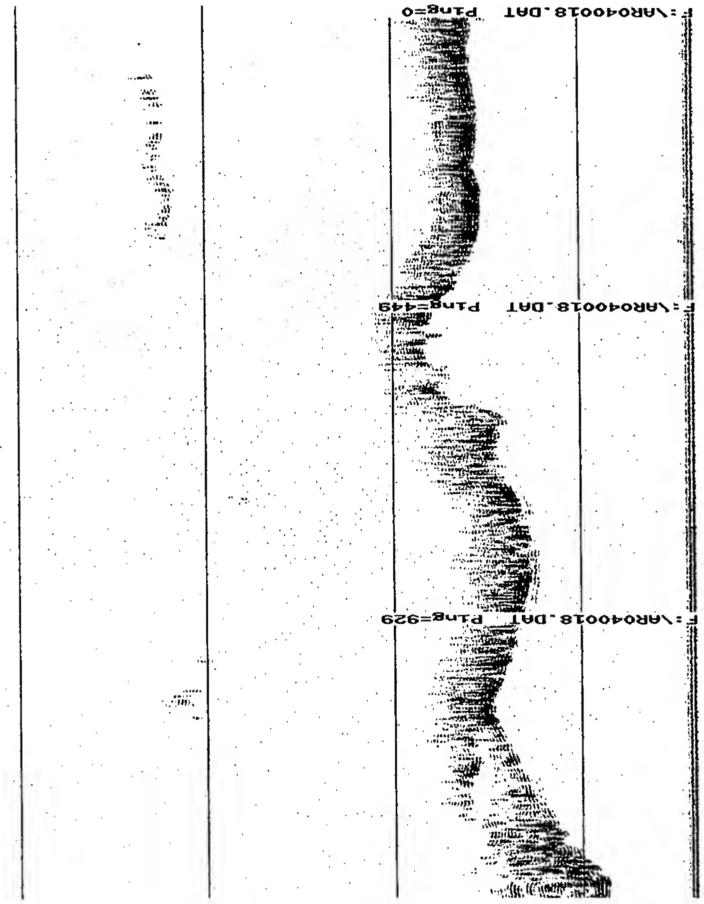
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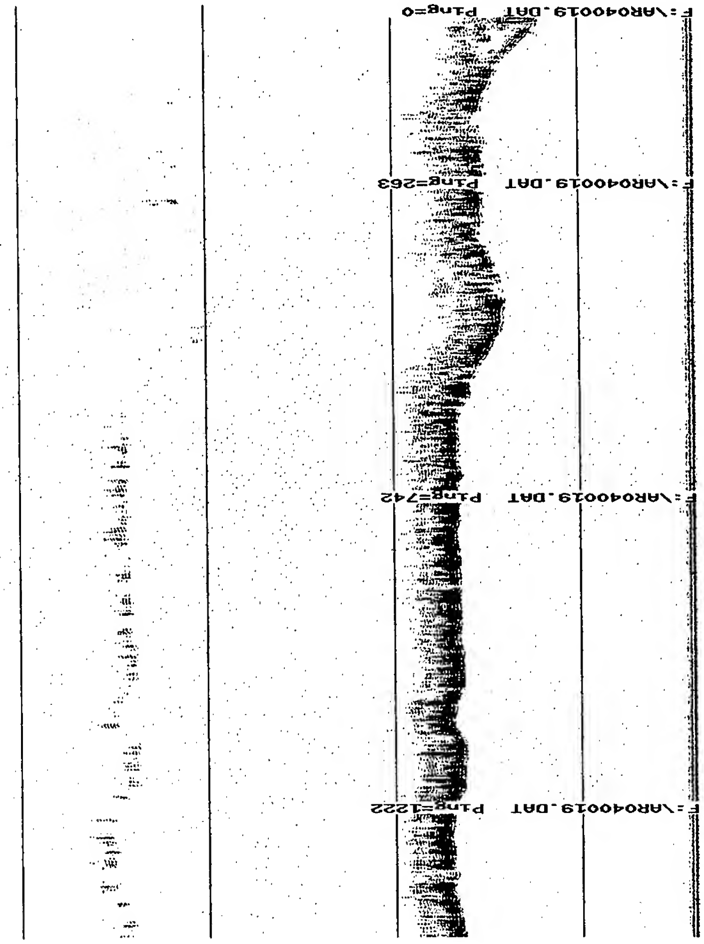
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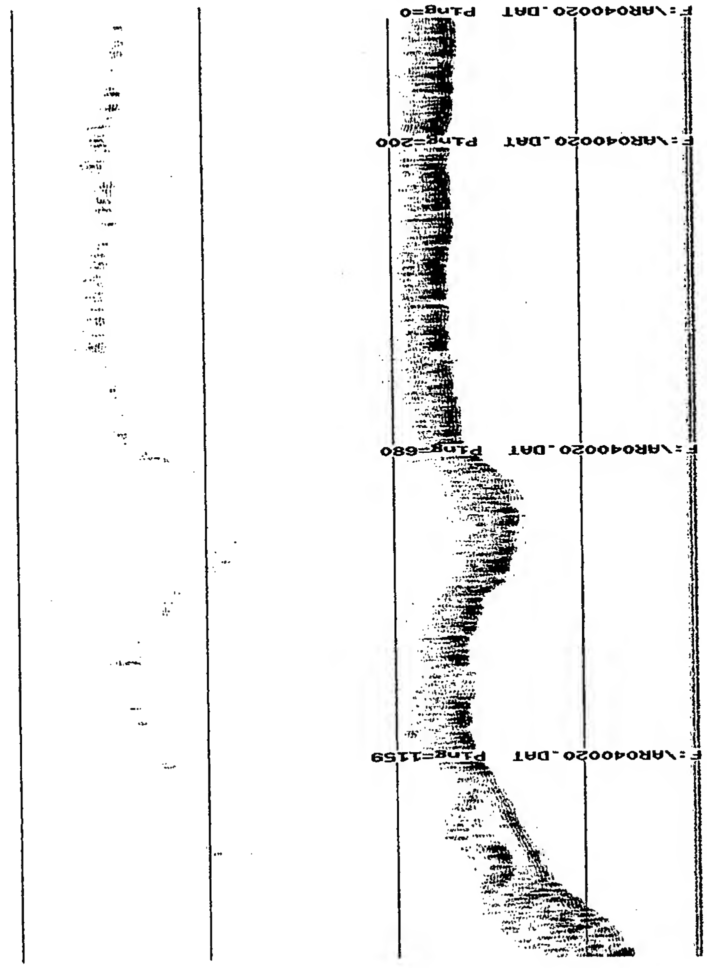
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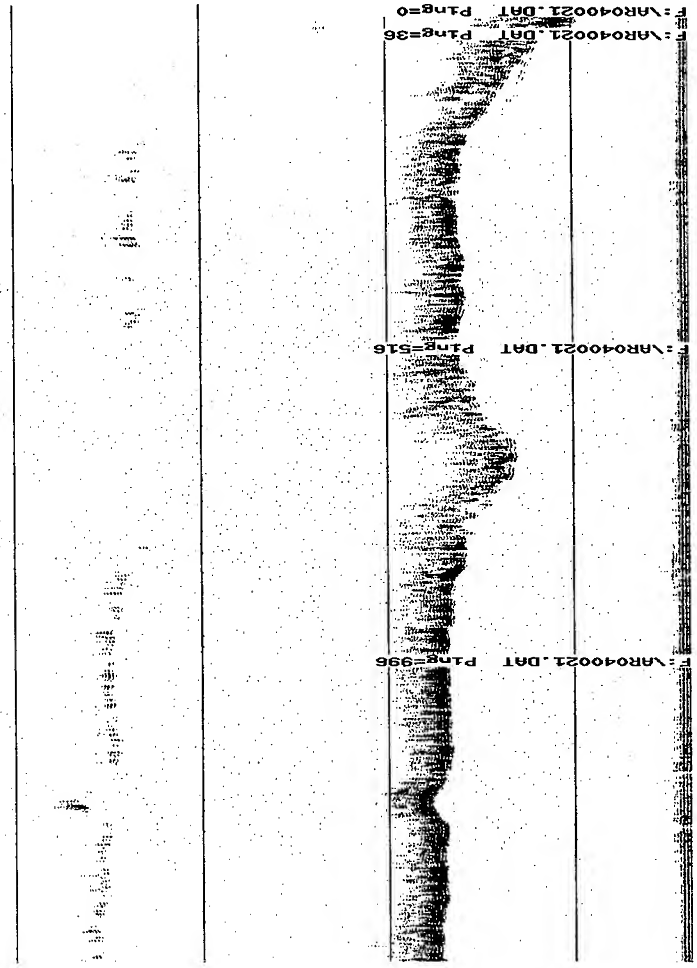
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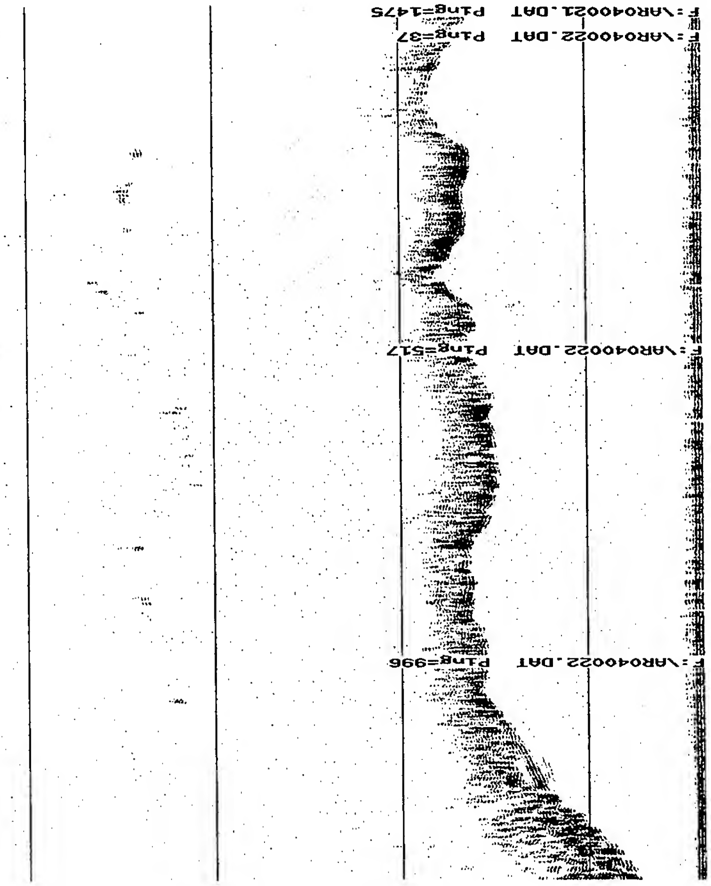
F:\AR040021.DAT Ping=1475
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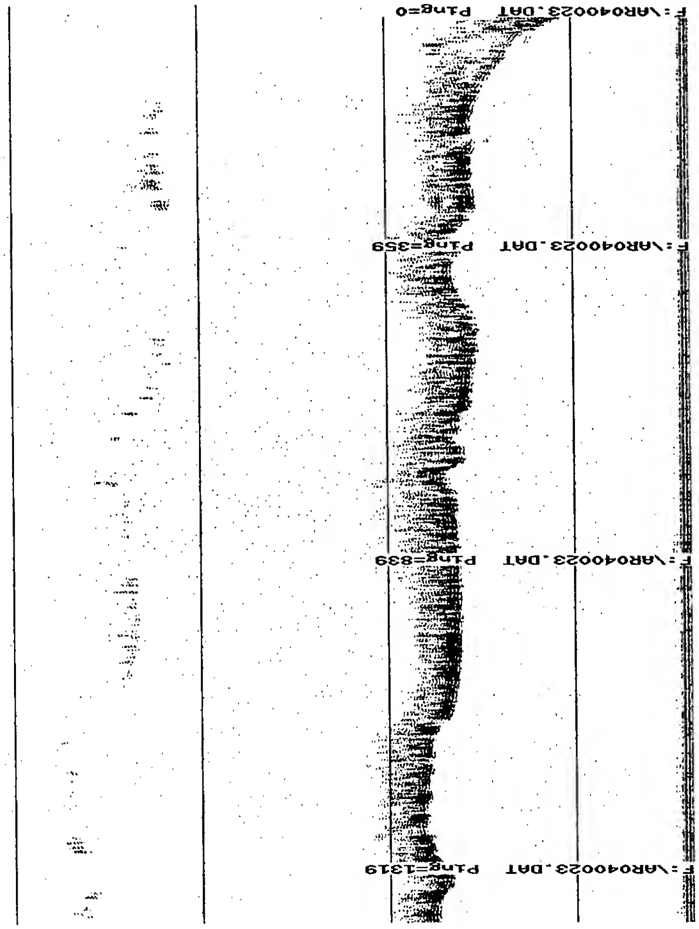
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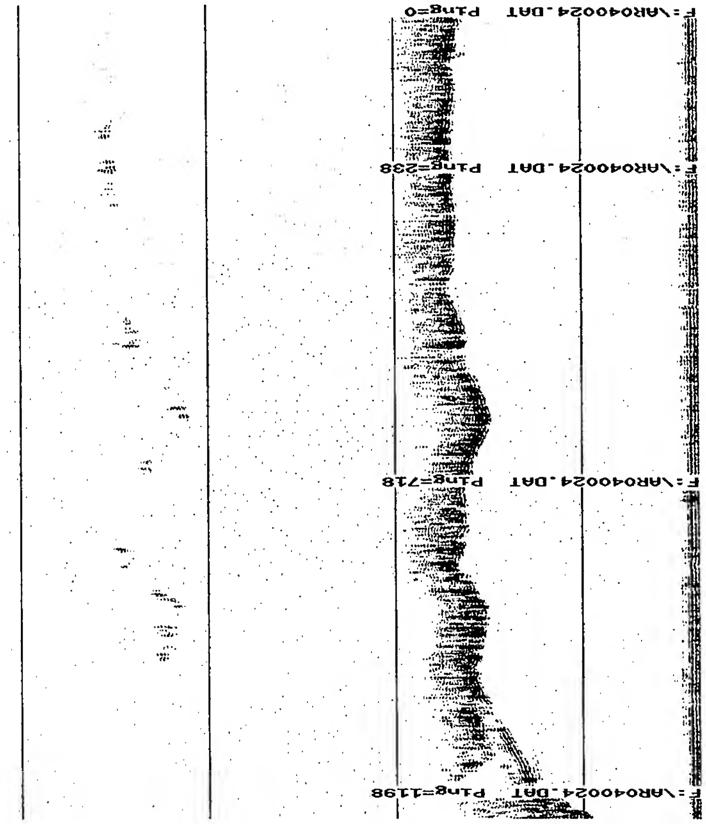
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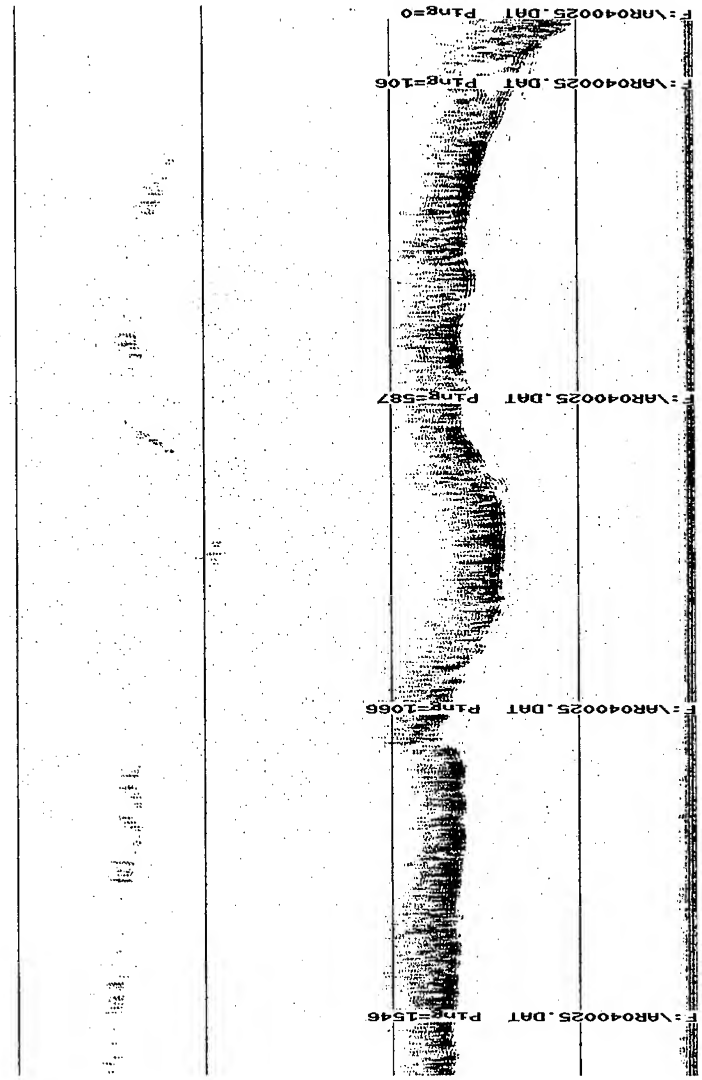
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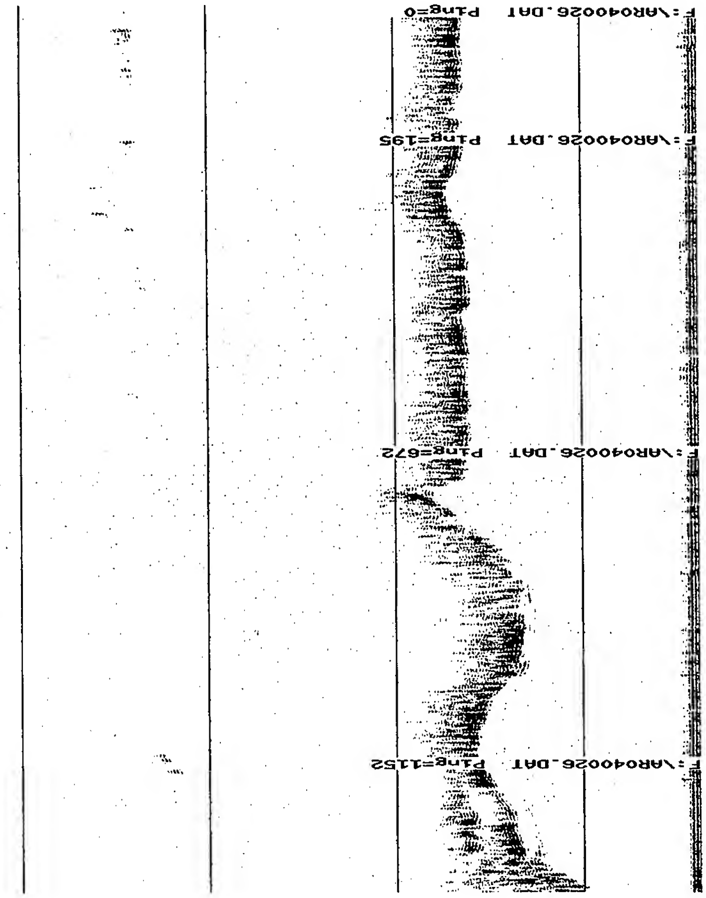
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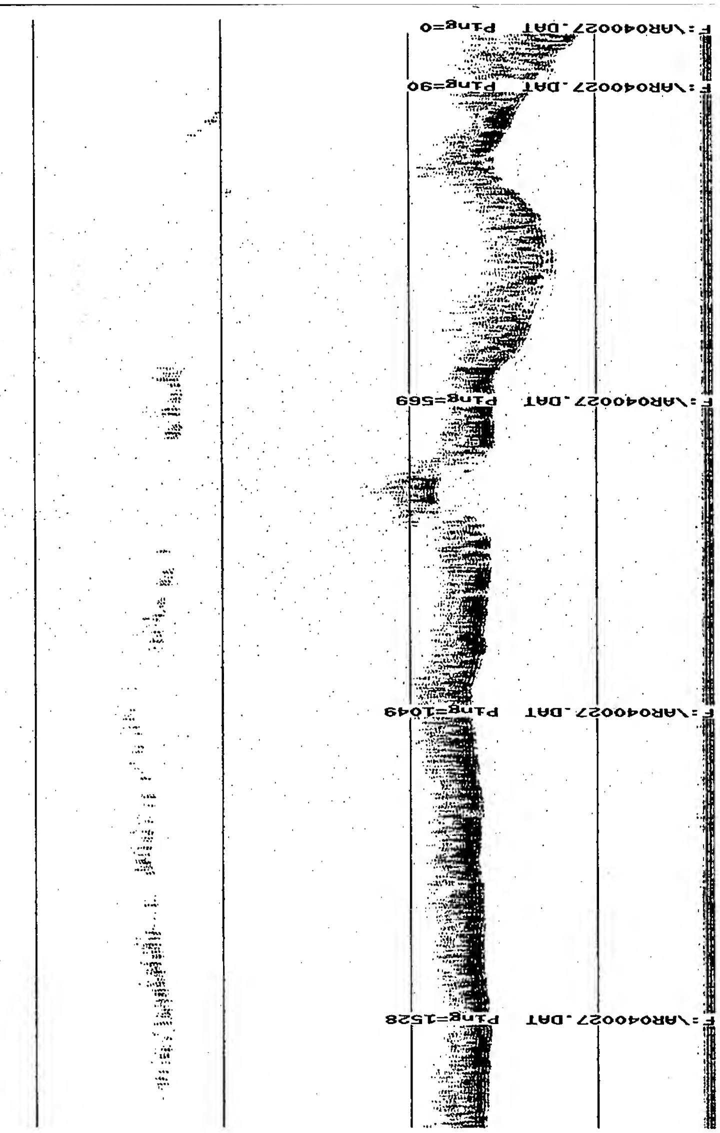
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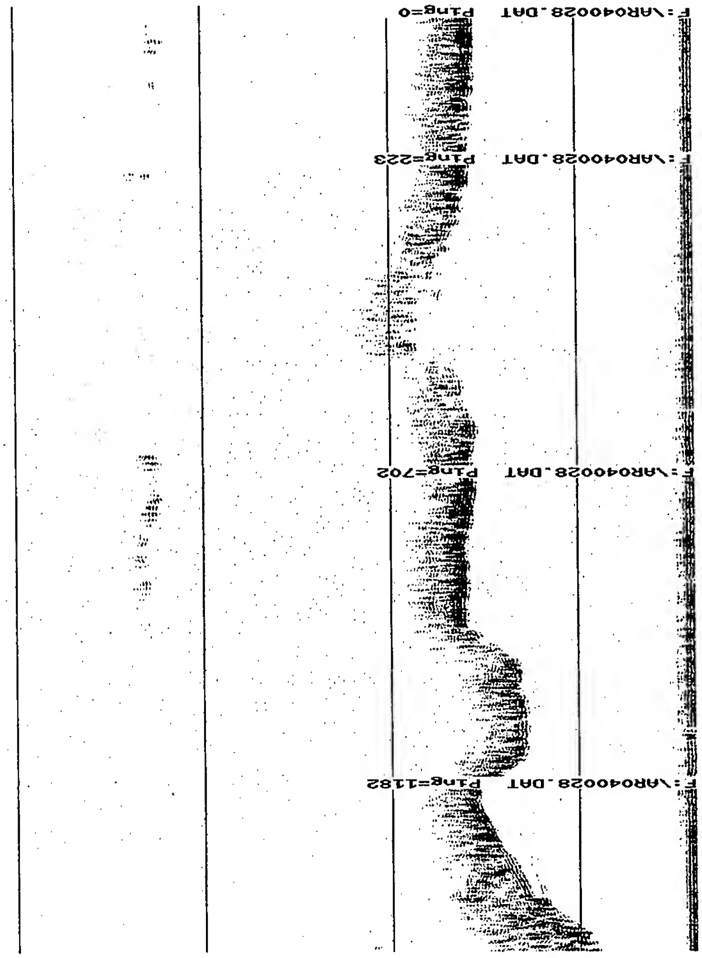
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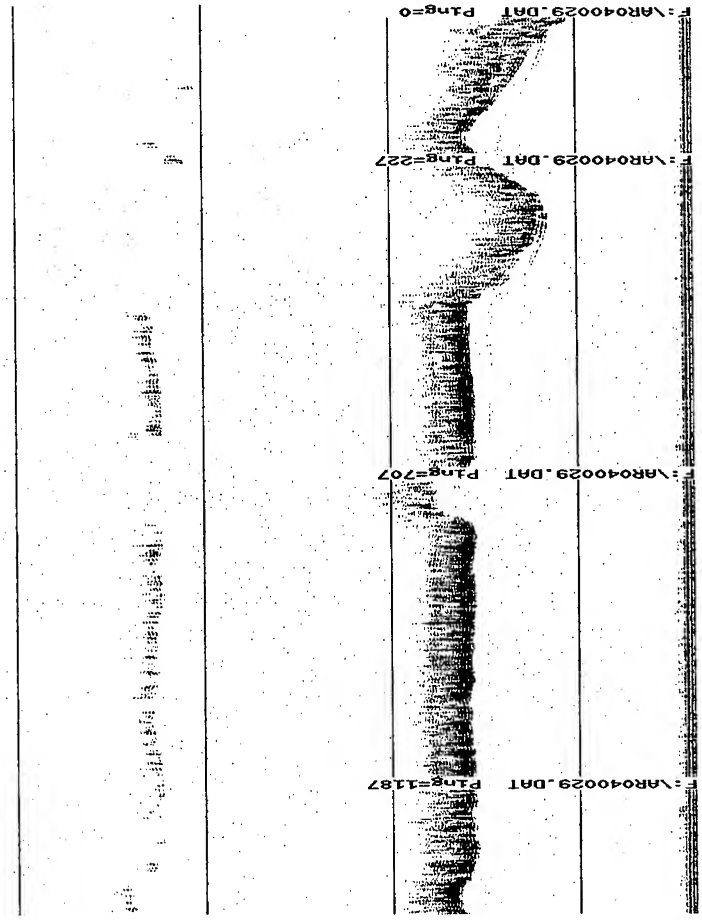
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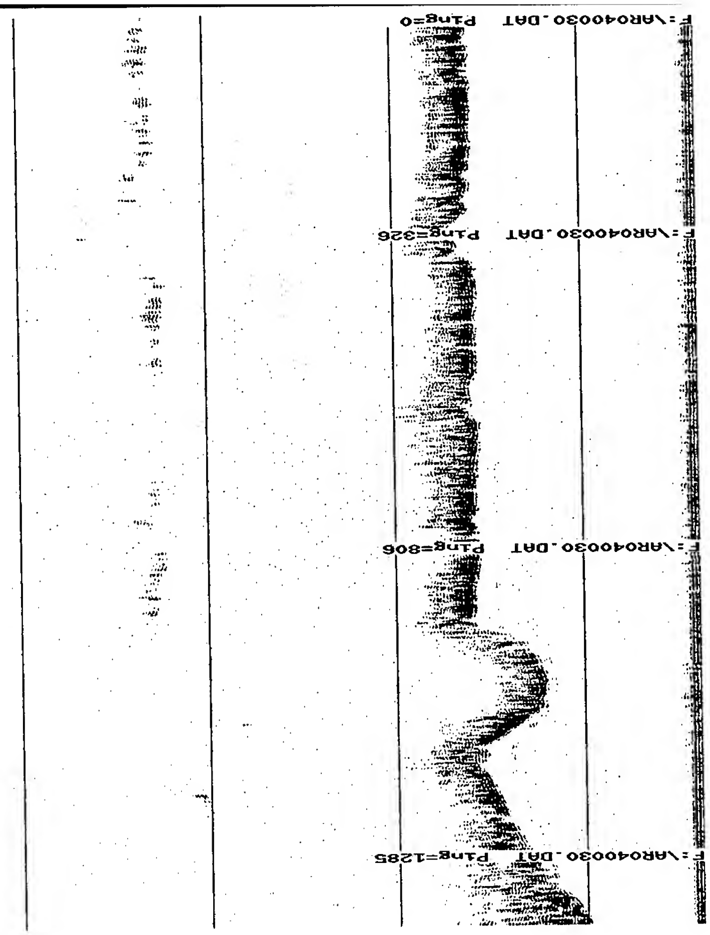
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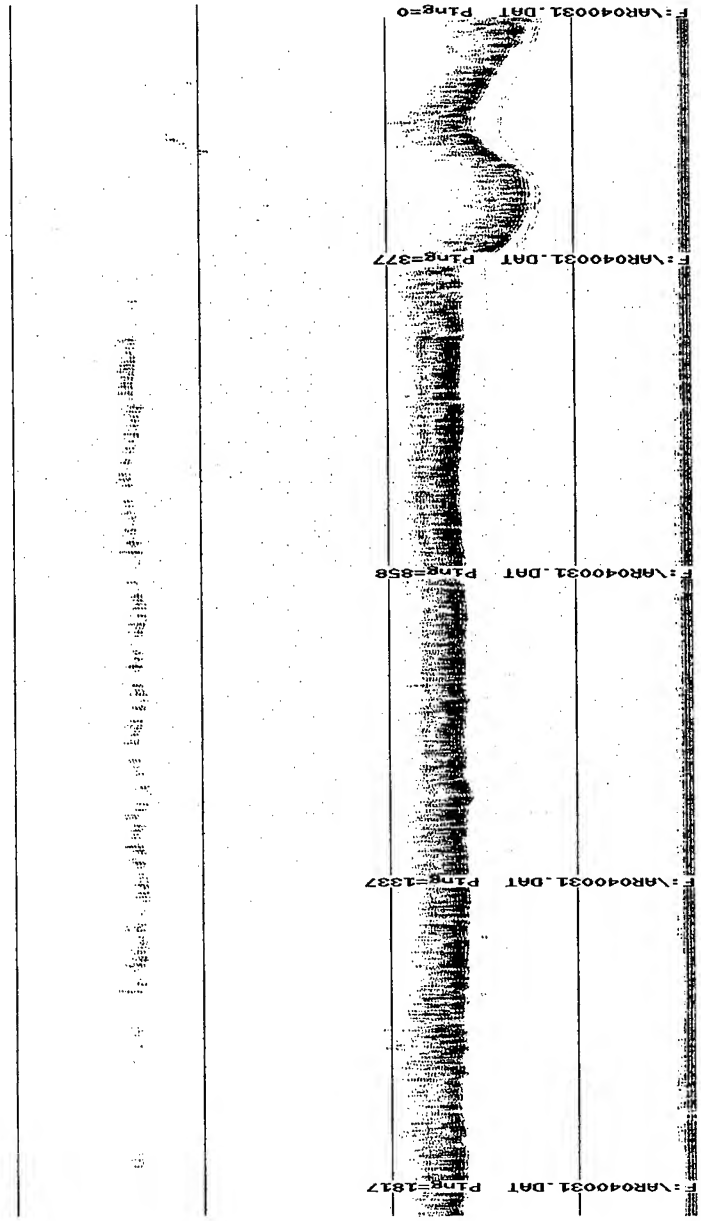
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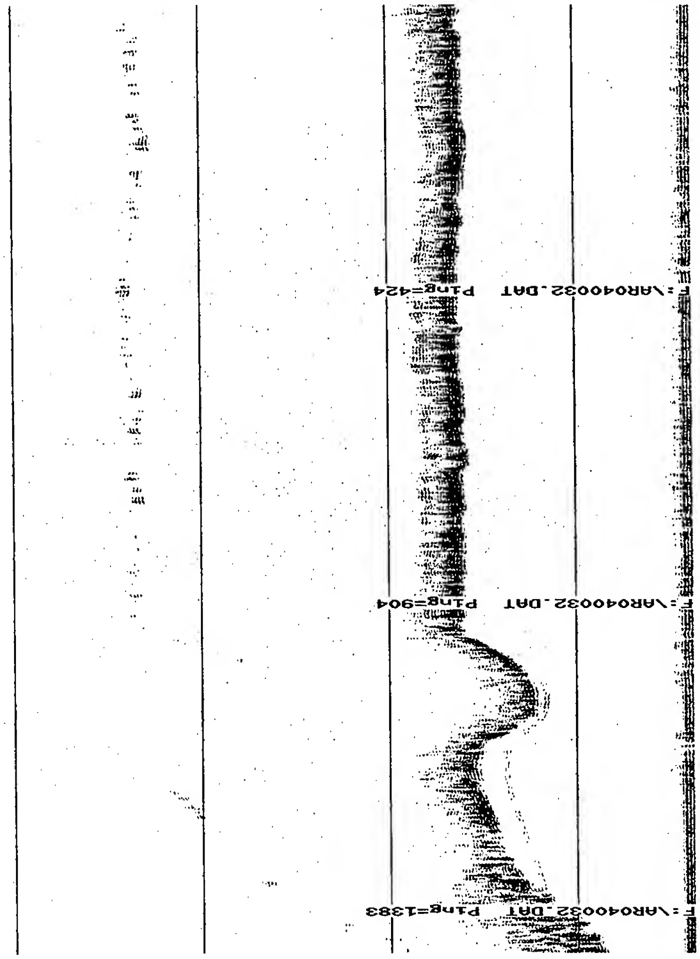
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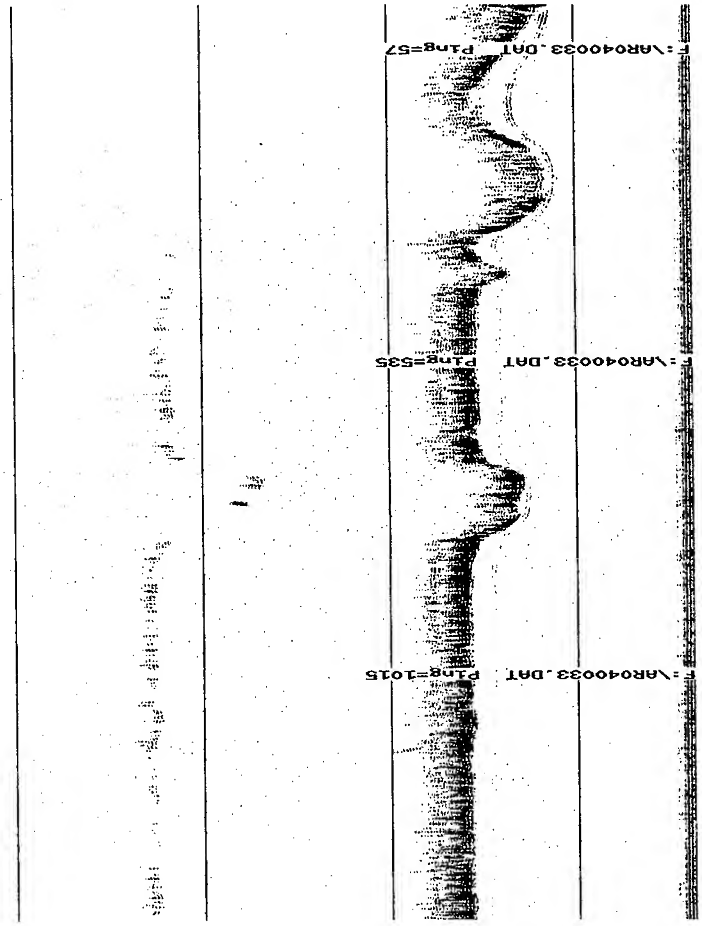
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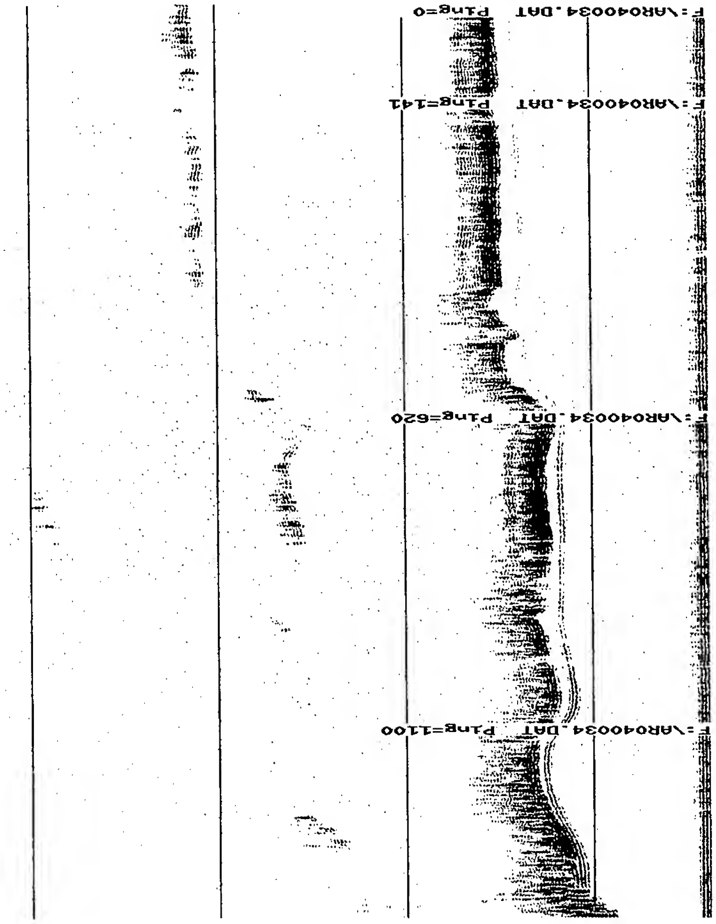
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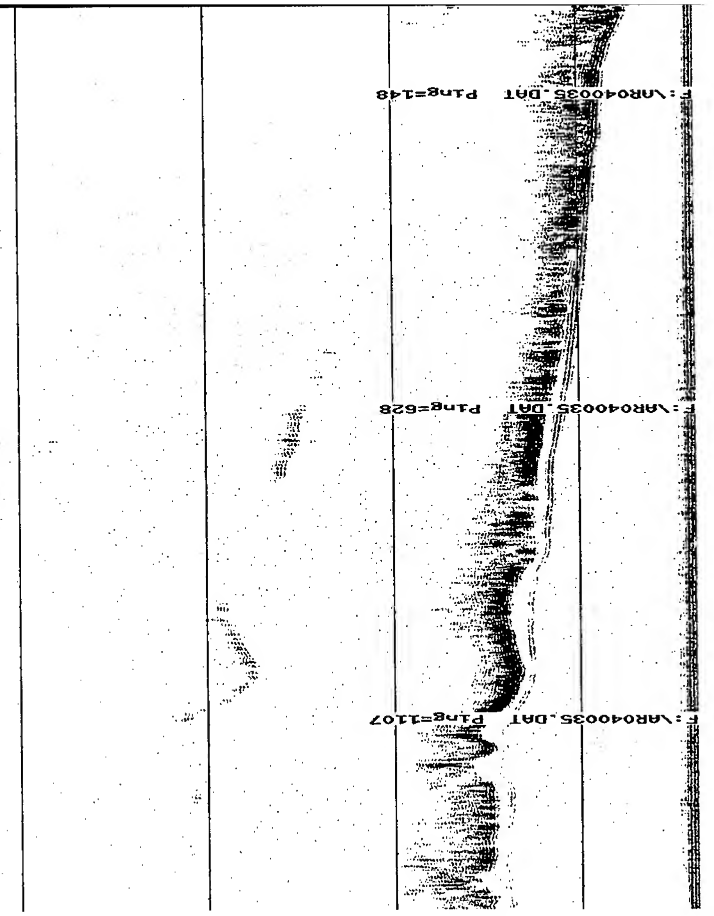
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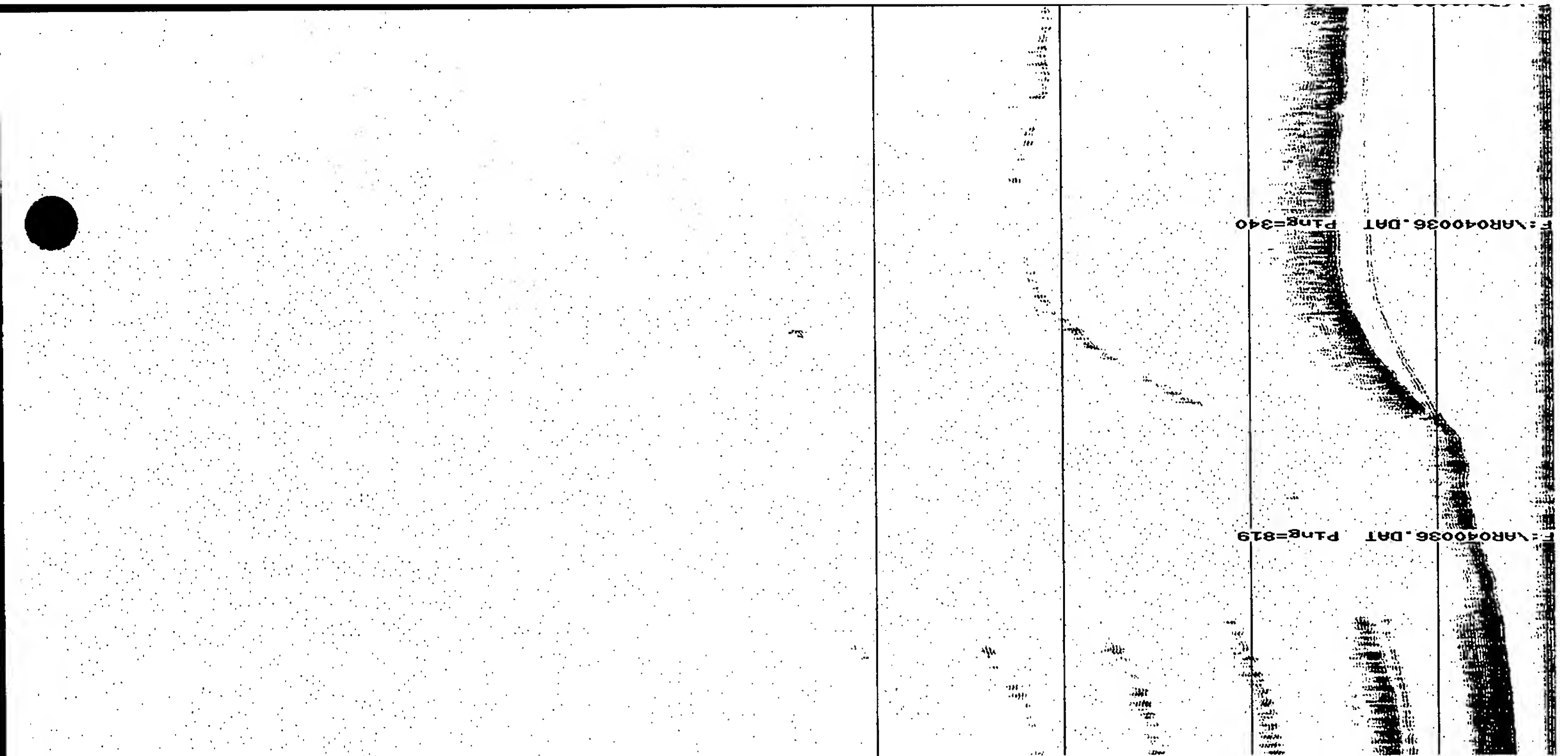
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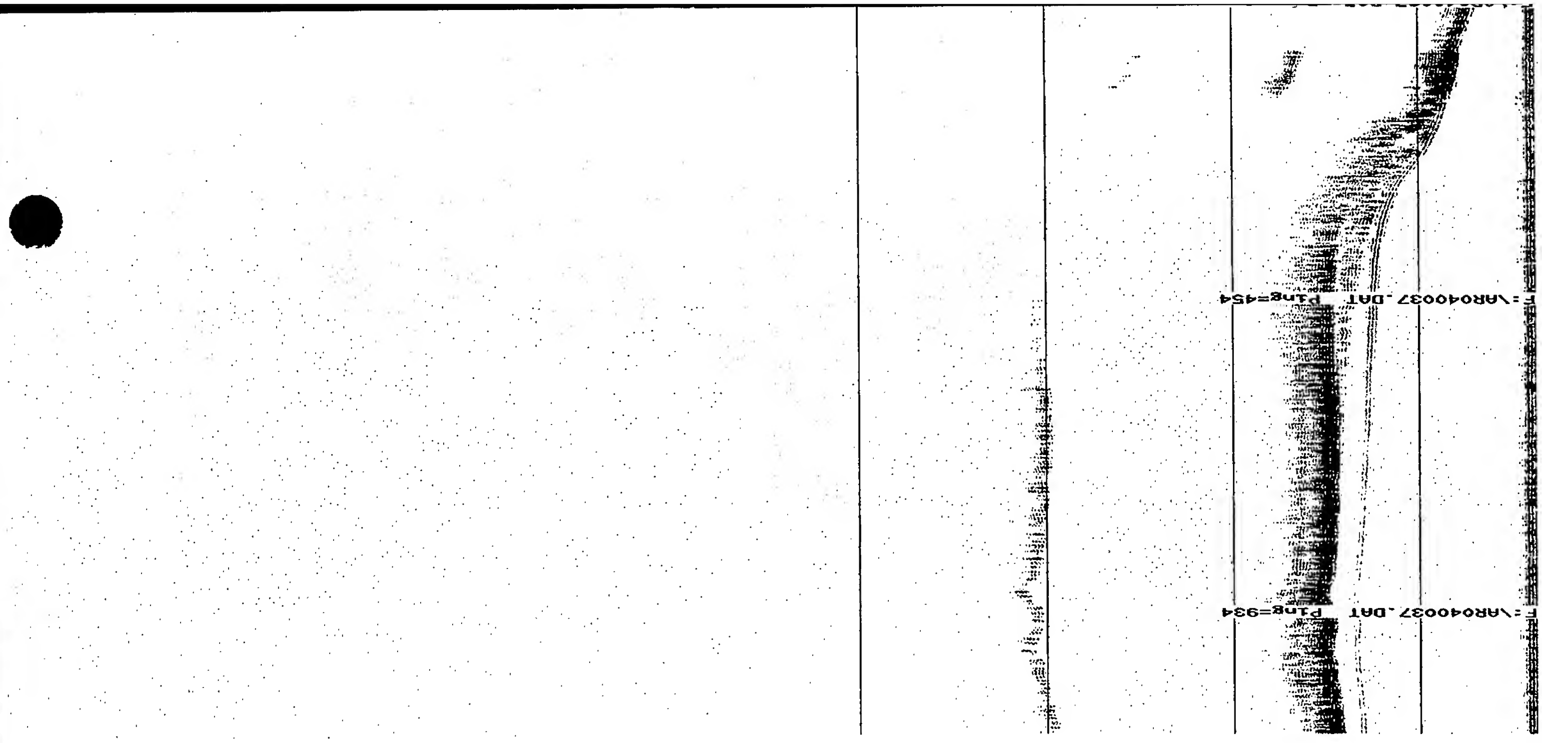
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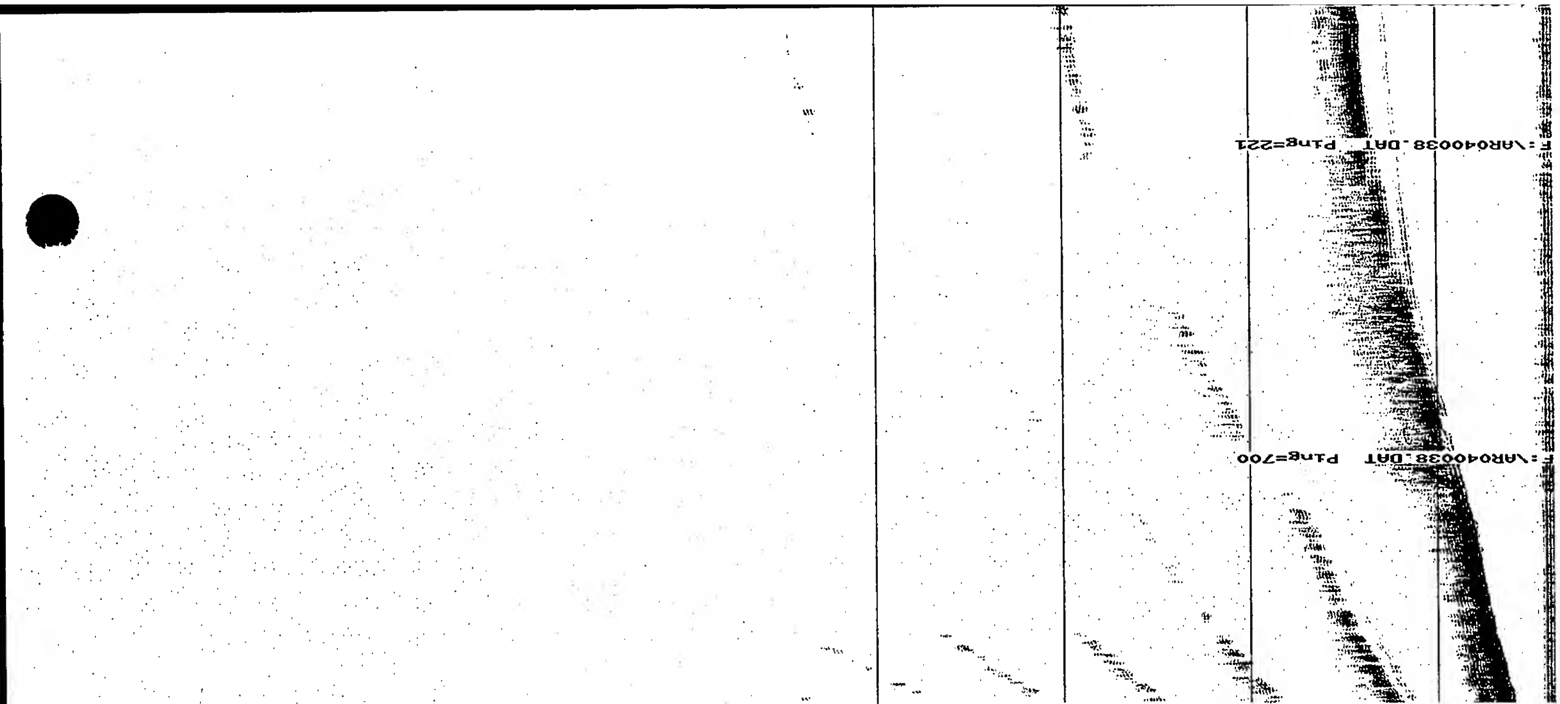
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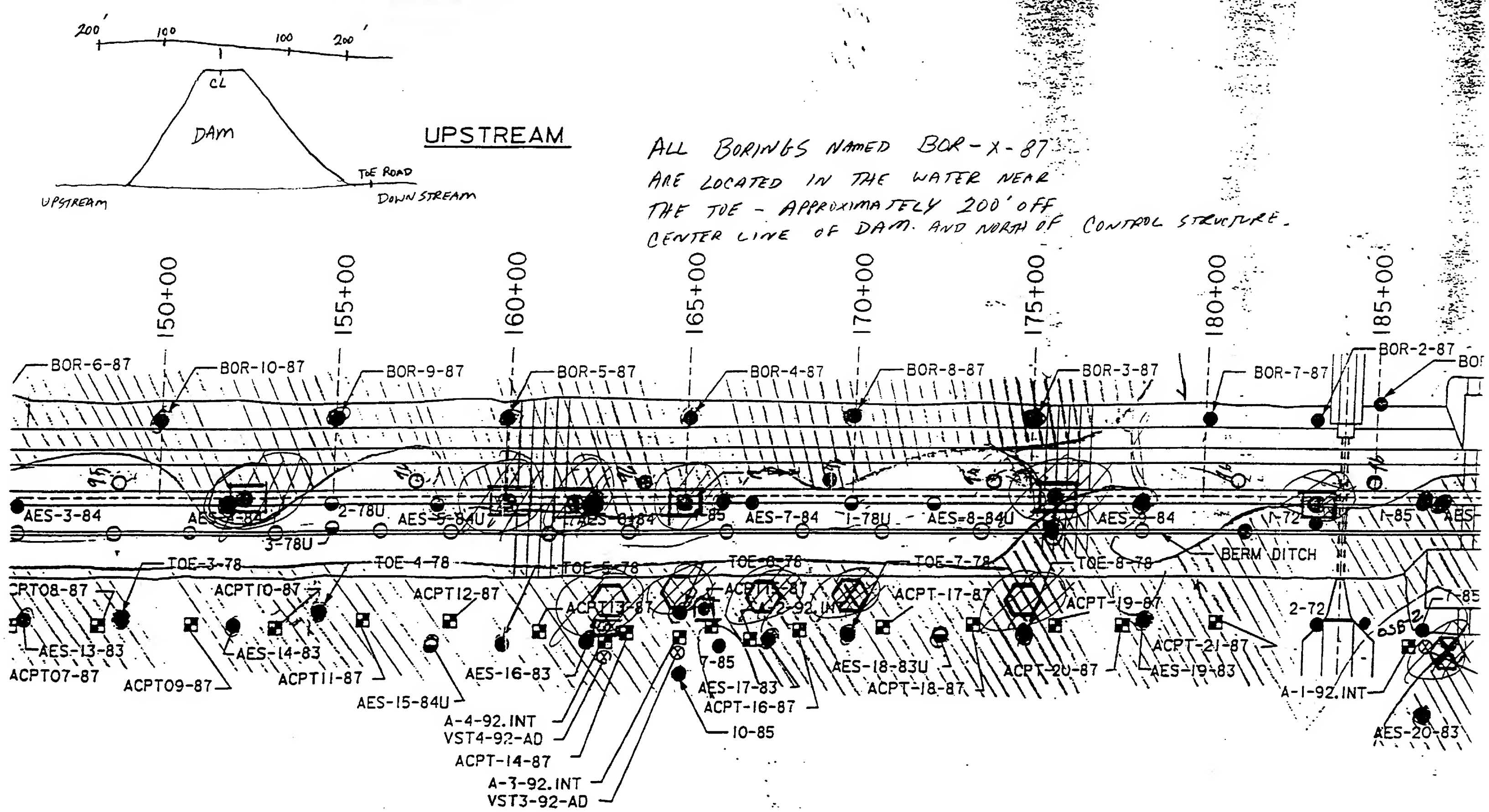
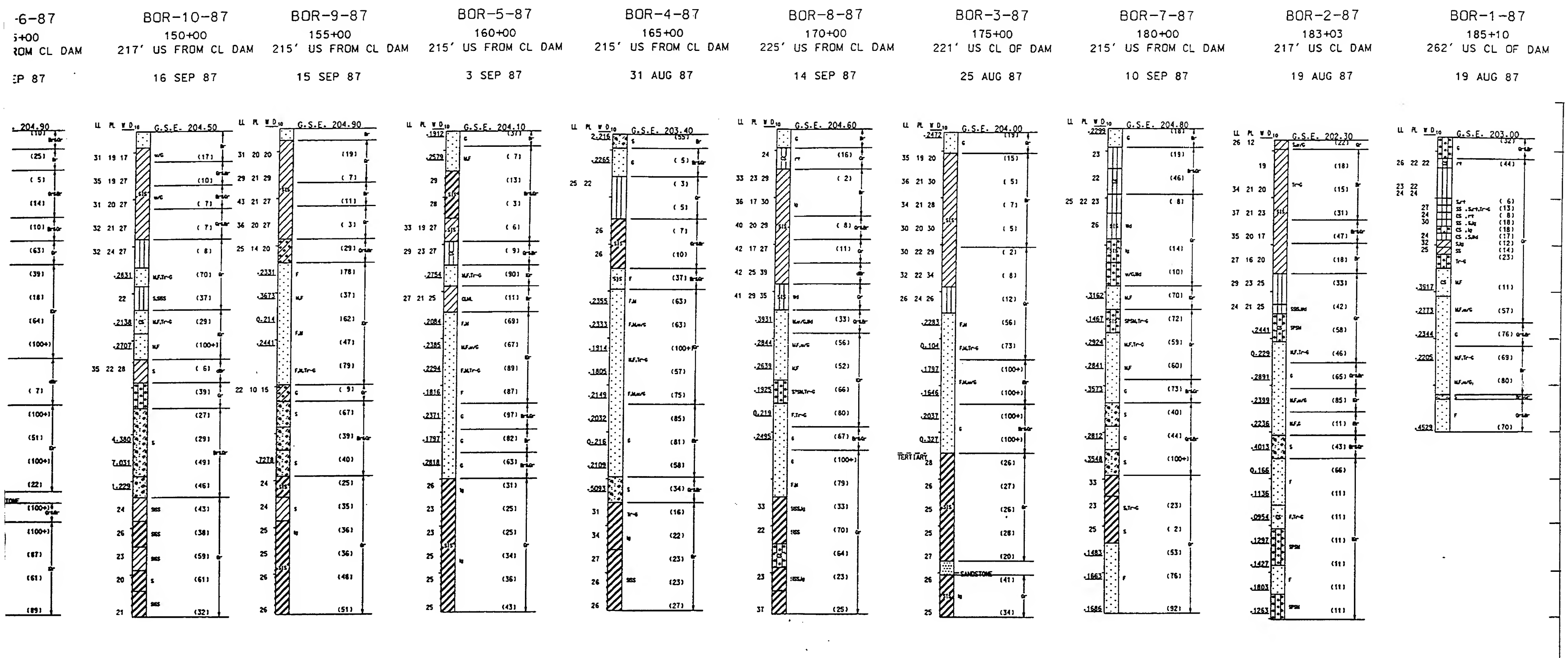
Appendix C
Available Core Information

ARKABUTLA DAM





-6-87
5+00
ROM CL DAM
EP 87
BOR-10-87
150+00
217' US FROM CL DAM
16 SEP 87
BOR-9-87
155+00
215' US FROM CL DAM
15 SEP 87
BOR-5-87
160+00
215' US FROM CL DAM
3 SEP 87
BOR-4-87
165+00
215' US FROM CL DAM
31 AUG 87
BOR-8-87
170+00
225' US FROM CL DAM
14 SEP 87
BOR-3-87
175+00
221' US CL OF DAM
25 AUG 87
BOR-7-87
180+00
215' US FROM CL DAM
10 SEP 87
BOR-2-87
183+03
217' US CL DAM
19 AUG 87
BOR-1-87
185+10
262' US CL OF DAM
19 AUG 87
G.S.E. 204.50
G.S.E. 204.90
G.S.E. 204.10
G.S.E. 203.40
G.S.E. 204.60
G.S.E. 204.00
G.S.E. 204.80
G.S.E. 202.30
G.S.E. 203.00
TERTIARY
SANDSTONE

C5

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
1	DATE	BORING_I	SAMPLE_I	TOP_DEP	BOT_DEP	TOP_ELE	BOT_ELE	STRAT_CI	STRAT_EI	CLASS_U	COLOR1	COLOR2	MOIS_CO	LL	PL	PI	SL	SP_GR	SPT_N	SHEAR_P	SHEAR_R	D10	D50	GRAVEL	SAND	FINES	CLAY	MAJCR_N	CONSIS	MSYM1	MSYM2	MSYM3	MSYM4
2																																	
3	08-19-87	BOR-01-871		0	1.5	203	201.5			SM									32														
4	08-19-87	BOR-01-872		5	6.5	198	196.5			ML			22	28	22	4			44			0.0039	0.02		1	99	13						
5	08-19-87	BOR-01-873		10	11.5	193	191.5			ML				23	22	1																	
6	08-19-87	BOR-01-874		11.5	13	191.5	190			ML			13																				
7	08-19-87	BOR-01-876		14.5	16	186.5	187			ML			27						13			0.0052	0.03		33	67	10						
8	08-19-87	BOR-01-877		16	17.5	187	185.5			ML			27						8			0.0048	0.02		11	89	10						
9	08-19-87	BOR-01-878		17.5	19	185.5	184			ML			27						18			0.0033	0.02		24	76	12						
10	08-19-87	BOR-01-879		19	20.5	184	182.5			SM									18														
11	08-19-87	BOR-01-8710		20.5	22	182.5	181			ML			22						17			0.0057	0.03		38	62	9						
12	08-19-87	BOR-01-8711		22	23.5	181	179.5			CL			32	30	20	10			12			0.0	0.02		12	88	19						
13	08-19-87	BOR-01-8712		23.5	25	179.5	178			CL			25	23	18	5			14			0.0	0.02		18	82	18						
14	08-19-87	BOR-01-8713		25	26.5	178	176.5			SM			28						23														
15	08-19-87	BOR-01-8714		31.5	42.4	171.5	170.6			SP			34						100			0.39	0.72	4	93	3							
16	08-19-87	BOR-01-8715		36.5	38	166.5	165			SP									57			0.28	1	7	90	3							
17	08-19-87	BOR-01-8716		41.5	43	161.5	160			SP									76			0.23	2.75	43	53	4							
18	08-19-87	BOR-01-8717		46.5	48	156.5	155			SP									69			0.22	0.54	8	91	3							
19	08-19-87	BOR-01-8718		51.5	53	151.5	150			SP			55						80														
20	08-19-87	BOR-01-87NSN		55	56	148	147			GP			56																				
21	08-19-87	BOR-01-8719		61.5	63	141.5	140			SP			60						70			0.45	1.19	20	80								
22	08-19-87	BOR-01-875		13	14.5	190	188.5			ML			14.5						6														
23	08-19-87	BOR-02-871		0	1.5	202.3	200.8	2.0		CL			2	26	12	14			26														
24	08-19-87	BOR-02-872		5	6.5	197.3	195.8			CL			19						18			0.004	0.05		7	93	10						
25	08-19-87	BOR-02-873		10	11.5	195.3	193.8			CL			20	34	21	13			15			0.0	0.02			100	21						
26	08-19-87	BOR-02-874		15	16.5	190.3	188.8			CL			23	37	21	16			31			0.0	0.02			100	20						
27	08-19-87	BOR-02-875		20	21.5	185.3	183.8			CL			17	35	20	15			47			0.0	0.02		1.6	98.4	20.7						
28	08-19-87	BOR-02-876		25	26	180.3	178.8	28.5		CL			20	27	16	11			18			0.0	0.02		16.6	83.4	17.5						
29	08-19-87	BOR-02-877		30	31.5	175.3	173.8	35.0		ML			25	29	23	6			33			0.0029	0.02		1.2	96.8	11.8						
30	08-19-87	BOR-02-878		35	36.5	170.3	168.8	37.0		ML			25	24	21	3			42			0.0026	0.03		33	67	11						
31	08-19-87	BOR-02-879		40	41.5	165.3	163.8	43.0		SP-SM									58			0.244	0.50	1	93	6							
32	08-19-87	BOR-02-8710		50	51.5	155.3	153.8			SP									46			0.229	0.53	3	93	4							
33	08-19-87	BOR-02-8711		50	51.5	155.3	153.8			SP									65			0.289	0.98	36	61	3							
34	08-19-87	BOR-02-8712		55	56.5	150.3	148.8			SP									85			0.240	0.42	8	90	2							
35	08-19-87	BOR-02-8713		60	61	145.3	144.3	63.0		SP									100			0.224	0.51	11	86	3							
36	08-19-87	BOR-02-8714		65	66.5	140.3	138.8	68.0		GP									43			0.401	4.88	51	47	2							
37	08-19-87	BOR-02-8715		70	71.5	135.3	133.8			SP									66			0.166	0.25		97	3							
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39	08-19-87	BOR-02-8717		80	81.3	125.3	124	83.0		SP									100			0.095	0.17		94	6							
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45	08-25-87	BOR-03-872		5	6.5	199	197.5			CL			20	35	19	16			15			0.0	0.02		1	99	20						
46	08-25-87	BOR-03-873		10	11.5	194	192.5			CL			30	36	21	15			5			0.0	0.01		2	98	30						
47	08-25-87	BOR-03-874		15	16.5	189	187.5			CL			28	34	21	13			7			0.0	0.02		3	97	25						
48	08-25-87	BOR-03-875		20	21.5	184	182.5			CL			30	30	20	10			2			0.0	0.02		3	97	24						
49	08-25-87	BOR-03-877		30	31.5	174	172.5	33		CL			34	32	22	10			8			0.0	0.01		3	97	20						
50	08-25-87	BOR-03-878		35	36.5	169	167.5	38.5		ML			28	26	24	2			12			0.0	0.02		14	86	10						
51	08-25-87	BOR-03-879		40	41.5	164	162.5			SP									56			0.228	0.32		97	3							
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55	08-25-87	BOR-03-8713		60	60.9	144	143.1			SP									100			0.204	1.03	37	58	5							
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59	08-25-87	BOR-03-8717		80	81.5	124	122.5			CH			25						26														
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62	08-25-87	BOR-03-87NSN		94	94.5	109	107.5	94.5		CH																							
63	08-25-87	BOR-03-8720		95	96.5	104	102.5			CH			26						41														
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66	08-31-87	BOR-04-872		5	6.5	198.4	196.9	9.0		SP									5			0.226	0.52	21	78	1							
67	08-31-87	BOR-04-873		10	11.5	193.4	191.9			ML				25	22	3			3														
68	08-31-87	BOR-04-874		15	16.5	188.4	186.9	18.0		ML									5														

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
69	08-31-87	BOR-04-875		20	21.5	183.4	181.9			CH			26						7														
70	08-31-87	BOR-04-876		25	28.5	178.4	176.9	28.5		CH			26						10														
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72	08-31-87	BOR-04-878		35	36.5	168.4	166.9			SP									63			0.235	0.38		98	2							
73	08-31-87	BOR-04-879		40	41.5	163.4	161.9			SP									63			0.233	0.47	9	87	4							
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76	08-31-87	BOR-04-8712		55	56	148.4	148.9			SP									75			0.214	0.34	1	95	4							
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79	08-31-87	BOR-04-8715		70	71.5	133.4	131.9	73.0		SP									58			0.21	1.84	30	88	4							
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81	08-31-87	BOR-04-8717		80	81.5	123.4	121.9	TERT		CH			31						16														
82	08-31-87	BOR-04-8718		85	86.5	118.4	116.9	88.5		CH			34						22														
83	08-31-87	BOR-04-8719		90	91.5	113.4	111.9			CH			27						23														
84	08-31-87	BOR-04-8720		95	96.5	108.4	106.9			CH			26						23														
85	08-31-87	BOR-04-8721		100	101.5	103.4	101.9	101.5		CH			26						27														
86	09-03-87	BOR-05-871		0	1.5	204.1	202.6			SP									37			0.191	0.48	21	77	2							
87	09-03-87	BOR-05-872		5	6.5	199.1	197.8	8.5		SP									7			0.257	0.53		100								
88	09-03-87	BOR-05-873		10	11.5	194.1	192.6			CH			29						13														
89	09-03-87	BOR-05-874		15	18.5	189.1	187.6	18.5		CH			28						3														
90	09-03-87	BOR-05-875		20	21.5	184.1	182.6	23.5		CL			27	33	19	14			6			0.0	0.01		3	97	30						
91	09-03-87	BOR-05-876		25	26.5	179.1	177.6	28.5		ML			27	29	23	6			9			0.0028	0.02		5	95	12						
92	09-03-87	BOR-05-877		30	31.5	174.1	172.6	33		SP									90			0.275	0.47	1	98	1							
93	09-03-87	BOR-05-878		35	38.5	169.1	167.6	38.5		CL-ML			25	27	21	6			11			0.0	0.02		10	90	14						
94	09-03-87	BOR-05-879		40	41.5	164.1	162.6			SP									69			0.208	0.35		99	1							
95	09-03-87	BOR-05-8710		45	46.5	159.1	157.6			SP									67			0.238	0.47	8	90	2							
96	09-03-87	BOR-05-8711		50	51.5	154.1	152.6			SP									89			0.229	0.36	1	97	2							
97	09-03-87	BOR-05-8712		55	56	149.1	147.6			SP									87			0.181	0.28		100								
98	09-03-87	BOR-05-8713		60	61.5	144.1	142.8			SP									97			0.237	2.4	37	60	3							
99	09-03-87	BOR-05-8714		65	66.5	139.1	137.6			SP									82			0.179	1.35	28	67	5							
100	09-03-87	BOR-05-8715		70	71.5	134.1	132.6	74.0		SP									63			0.281	2.63	23	75	2							
101	09-03-87	BOR-05-8716		75	76.5	129.1	127.6	TERT		CH			26						31														
102	09-03-87	BOR-05-8717		80	81.5	124.1	122.6			CH			23						25														
103	09-03-87	BOR-05-8718		85	88.5	119.1	117.6			CH			23						25														
104	09-03-87	BOR-05-8719		90	91.5	114.1	113.6			CH			25						34														
105	09-03-87	BOR-05-8720		95	96.5	109.1	107.6			CH			25						36														
106	09-03-87	BOR-05-8721		101	102.5	104.1	102.6	102.5		CH			25						43														
107	09-09-87	BOR-06-871		0	1.5	204.9	203.4	4.0		SP									10			0.249	2.09	37	61	2							
108	09-09-87	BOR-06-872		5	6.5	199.9	198.4	8.5		CL-ML			23	28	22	6			25			0.0	0.01		1	99	15						
109	09-09-87	BOR-06-873		10	11.5	194.9	193.4			CL			26	35	17	18			5			0.0	0.01		10	90	29						
110	09-09-87	BOR-06-874		15	16.5	189.9	188.4			CL			24	37	18	19			14			0.0	0.01		6	94	31						
111	09-09-87	BOR-06-875		20	21.5	184.9	183.4	23.5		CL			28	37	22	15			10			0.0	0.02		1	99	23						
112	09-09-87	BOR-06-876		25	26.5	179.9	173.4			SP									63			0.157	0.26		97	3							
113	09-09-87	BOR-06-877		30	31.5	174.9	173.5			SP									39			0.373	0.55		99	1							
114	09-09-87	BOR-06-878		35	36.5	169.9	188.4			SP									18			0.193	0.35		96	4							
115	09-09-87	BOR-06-879		40	41.5	164.9	163.4			SP									18			0.179	0.38	1	95	4							
116	09-09-87	BOR-06-8710		45	46.5	159.9	158.4	48.5		SP									100			0.287	0.41	1	98	1							
117	09-09-87	BOR-06-8711		50	51.5	154.9	153.4			CL			35	50	24	28						0.0052	0.05		42	58	10						
118	09-09-87	BOR-06-8712		55	56.5	149.9	148.4	58.5		CL			32	46	20	28			7			0.0020	0.03	8	18	74	13						
119	09-09-87	BOR-06-8713		60	60.5	144.9	143.4			SP									100			0.305	3.80	43	54	3							
120	09-09-87	BOR-06-8714		65	66.5	139.9	138.4			SP									51			0.282	4.65	50	48	2							
121	09-09-87	BOR-06-8715		70	70.9	134.9	133.4			SP									100			0.19	0.29		98	2							
122	09-09-87	BOR-06-8716		75	76.5	129.9	128.4	77.0		SP									22			0.2165	0.36	3	96	1							
123	09-09-87	BOR-06-87NSN		78.5	79.5	124.9	123.4	79.5		GP																							
124	09-09-87	BOR-06-8717		80	80.5	119.9	118.4	83.5		GP									100			0.179	8.12	83	37								
125	09-09-87	BOR-06-8718		85	86	114.9	113.4			SP									100			0.179	0.3		98	2							
126	09-09-87	BOR-06-8719		90	91.5	109.9	108.4			SP									87			0.166	0.30		96	4							
127	09-09-87	BOR-06-8720		95	96.5	104.9	103.4			SP									61			0.188	0.28		98	2							
128	09-09-87	BOR-06-8721		102	103.5	99.9	98.4	103.5		SP									89			0.151	0.24		97	3							
129	09-10-87	BOR-07-871		0	1.5	204.8	203.3	4.0		SP									18			0.229	0.63	26.8	71.2	2.0							
130	09-10-87	BOR-07-872		5	8.5	199.8	198.8	8.5		ML			23						19			0.0019	0.02		3.0	97.0	15.3						
131	09-10-87	BOR-07-873		10	11.5	194.8	193.3	14.0		ML			22						48			0.0028	0.02		1.8	98.4	12.5						
132	09-10-87	BOR-07-874		15	16.5	189.8	188.3	18.0		ML			23	25	22	3			8			0.0	0.02		2.8	97.4	18.0						
133	09-10-87	BOR-07-875		20	21.5	184.8	183.3	23.5		ML			26									0.0	0.02		7.2	92.8	15.2						
134	09-10-87	BOR-07-876		25	26.5	179.8	178.3	28.5		SM									14														
135	09-10-87	BOR-07-877		30	31.5	174.8	173.3	33.5		SM									10														
136	09-10-87	BOR-07-878		35	36.5	169.8	168.3	38.5		SP									70			0.318	0.48		96.8	3.2							

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
137	09-10-87	BOR-07-87	9	40	41.5	164.8	163.3	43.5		SM									72			0.146	0.41	5.8	87.4	6.6							
138	09-10-87	BOR-07-87	10	45	46.5	159.8	158.3			SP									59			0.292	0.51	0.3	96.4	3.3							
139	09-10-87	BOR-07-87	11	50	51.5	154.8	153.3			SP									60			0.284	0.49		96.5	3.5							
140	09-10-87	BOR-07-87	12	55	58.5	149.8	148.3	58.5		SP									73			0.357	4.21	48.0	48.7	3.3							
141	09-10-87	BOR-07-87	13	60	61.5	144.8	143.3	63.5		GP									40														
142	09-10-87	BOR-07-87	14	65	66.5	139.8	138.3	68.5		SP									44			0.281	4.02	46.9	49.6	3.5							
143	09-10-87	BOR-07-87	15	70	71.4	134.8	133.3	74.0		GP									100			0.354	5.82	54.6	42.4	3.0							
144	09-10-87	BOR-07-87	16	75	76.5	129.8	128.3	78.5		CH			33																				
145	09-10-87	BOR-07-87	17	80	81.5	124.8	123.3			CH			23						23														
146	09-10-87	BOR-07-87	18	85	86.5	119.8	118.3	88.5		CH			25						2														
147	09-10-87	BOR-07-87	19	90	91.5	114.8	113.3			SP									53			0.148	0.23		97.9	2.1							
148	09-10-87	BOR-07-87	20	95	96.5	109.8	108.3			SP									76			0.166	0.25		98.1	1.9							
149	09-10-87	BOR-07-87	21	102	103	104.6	103.3	103.5		SP									92			0.168	0.23		98.3	1.7							
150	09-14-87	BOR-08-87	NSN	0	3.5	204.6	201.5	4.0		SP																							
151	09-14-87	BOR-08-87	1	5	6.5	199.6	198.1	8.5		ML			24						16			0.0	0.02		0.8	97.4	24.0						
152	09-14-87	BOR-08-87	2	10	11.5	194.6	193.1			CL			29	33	23	10			2			0.0	0.02		1.6	98.4	21.3						
153	09-14-87	BOR-08-87	3	15	16.5	189.6	188.1			CL			30	36	17	19						0.0	0.01		5.6	94.4	31.4						
154	09-14-87	BOR-08-87	4	20	21.5	184.6	183.1			CL			29	40	20	20			8			0.0	0.01		4.8	95.2	41.7						
155	09-14-87	BOR-08-87	5	25	26.5	179.6	178.1			CL			27	42	17	25			11			0.0	0.01		0.2	99.8	34.3						
156	09-14-87	BOR-08-87	6	30	31.5	174.6	173.1	33.0		CL			39	42	25	17						0.0	0.01		0.6	99.2	23.9						
157	09-14-87	BOR-08-87	7	35	36.5	169.6	168.1	38.5		ML			35	41	29	12						0.0016	0.02		0.6	99.4	16.2						
158	09-14-87	BOR-08-87	8	40	41.5	164.6	163.1			SP									33			0.3931	0.71	8.8	88.3	2.9							
159	09-14-87	BOR-08-87	9	45	46.5	159.6	158.1			SP									56			0.2844	0.48	0.9	97.2	1.9							
160	09-14-87	BOR-08-87	10	50	51.5	154.6	153.6	53.5		SP									52			0.2639	0.44		98.1	1.9							
161	09-14-87	BOR-08-87	11	55	56.5	149.6	148.1	58.5		SM									66			0.1925	0.41	8.4	86.4	5.2							
162	09-14-87	BOR-08-87	12	60	61.5	144.6	143.1			SP									60			0.2190	0.36	9.2	89.0	1.6							
163	09-14-87	BOR-08-87	13	65	66.5	139.6	138.1			SP									67			0.2495	0.88	27.5	69.1	3.4							
164	09-14-87	BOR-08-87	14	70	71.4	134.6	133.1			SP									100			0.1736	0.39	21.1	75.6	3.2							
165	09-14-87	BOR-08-87	15	75	76.5	129.6	128.1	78.5		SP									79			0.3837	0.51		97.2	2.6							
166	09-14-87	BOR-08-87	18	80	81.5	124.6	124.1	TERT		CH			33						33														
167	09-14-87	BOR-08-87	17	85	86.5	119.6	118.1	88.5		CH			22						70														
168	09-14-87	BOR-08-87	18	90	91.5	114.6	113.1	93.5		SM									64														
169	09-14-87	BOR-08-87	19	95	96.5	109.6	108.1			CH			23						23														
170	09-14-87	BOR-08-87	20	102	103.5	104.6	103.1	103.5		CH			37						25														
171	09-15-87	BOR-09-87	NSN	0	2.5	204.9	202.4	2.5		SP																							
172	09-15-87	BOR-09-87	1	5	8.5	199.9	198.4			CL			20	31	20	11			19			0.0	0.02		0.7	99.3	21.7						
173	09-15-87	BOR-09-87	2	10	11.5	194.9	193.4			CL			29	29	21	8			19			0.0	0.01		3.0	97.0	26.4						
174	09-15-87	BOR-09-87	3	15	16.5	189.9	188.4			CL			27	43	21	22			11			0.0	0.01		5.4	94.6	28.3						
175	09-15-87	BOR-09-87	4	20	21.5	184.9	183.4	23.5		CL			27	36	20	16			3			0.0	0.01		2.0	98.0	22.1						
176	09-15-87	BOR-09-87	5	25	26.5	179.9	178.4	28.5		SC			20	25	14	11			29			0.0067	0.19		73.4	26.6	9.3						
177	09-15-87	BOR-09-87	6	30	31.5	174.9	173.4			SP									78			0.2331	0.33		98.8	1.4							
178	09-15-87	BOR-09-87	7	35	36.5	169.9	168.4			SP									37			0.3673	0.63	0.9	97.2	1.9							
179	09-15-87	BOR-09-87	8	40	41.5	164.9	163.4			SP									62			0.2140	0.32		98.1	1.9							
180	09-15-87	BOR-09-87	9	45	46.5	159.9	158.4			SP									47			0.2441	0.47		97.0	3.0							
181	09-15-87	BOR-09-87	10	50	51.5	154.9	153.4	54.5		SP									79			0.1360	0.59	0.7	93.1	6.2							
182	09-15-87	BOR-09-87	11	55	56.5	149.9	148.4	58.0		SC			15	22	10	12			9			0.0	0.05		44.4	55.6	18.7						
183	09-15-87	BOR-09-87	12	60	81.5	144.9	143.4			GP									67			0.3750	3.97	46.7	50.1	3.2							
184	09-15-87	BOR-09-87	13	65	66.5	139.9	138.4	68.5		GP									39														
185	09-15-87	BOR-09-87	14	70	71.5	134.9	133.4	74.0		GP									40			0.7278	6.89	60.9	37.3	1.9							
186	09-15-87	BOR-09-87	15	75	76.5	129.9	128.4	78.5		CH			24						25														
187	09-15-87	BOR-09-87	16	80	81.5	124.9	123.4	83.5		CH			24	58	19	39			35														
188	09-15-87	BOR-09-87	17	85	86.5	119.9	118.4			CH			25						36														
189	09-15-87	BOR-09-87	18	90	91.5	114.9	113.4			CH			25						36														
190	09-15-87	BOR-09-87	19	95	96.5	109.9	108.4			CH			26						48														
191	09-15-87	BOR-09-87	20	102	103.5	104.9	103.4	103.5		CH			26						51														
192	09-16-87	BOR-10-87	NSN	0	3.5	204.5	201	3.5		SP																							
193	09-16-87	BOR-10-87	1	5	8.5	199.5	193			CL			17	31	19	12			17			0.0	0.02		1.4	98.6	17.2						
194	09-16-87	BOR-10-87	2	10	11.5	194.5	193			CL			27	35	19	16			10			0.0	0.01		6.4	93.8	33.2						
195	09-16-87	BOR-10-87	3	15	16.5	189.5	188			CL			27	31	20	11			7			0.0	0.02		6.4	93.8	19.4						
196	09-16-87	BOR-10-87	4	20	21.5	184.5	183	23.0		CL			27	32	21	11			7			0.0	0.02		1.4	98.6	19.0						
197	09-16-87	BOR-10-87	5	25	26.5	179.5	178	29.0		ML			27	32	24	8			8			0.0	0.02		2.0	98.0	16.1						
198	09-16-87	BOR-10-87	6	30	31.5	174.5	173	33.0		SP									70			0.2831	0.45	0.5	97.7	1.8							
199	09-16-87	BOR-10-87	8	40	41.5	164.5	163	43.0		SP									29			0.2138	0.72	2.5	93.0	4.5							
200	09-16-87	BOR-10-87	9	45	45.9	159.5	158	48.5		SP									100			0.2707	0.45	0.2	97.5	2.2							
201	09-16-87	BOR-10-87	10	50	51.5	154.5	153	53.5		CL			28	35	22	13			6			0.0038	0.03		27.0	73.0	12.0						
202	09-16-87	BOR-10-87	11	55	56.5	149.5	148	59.0		SM									39														
203	09-16-87	BOR-10-87	12	60	61.5	144.5	143			GP									27														
204	09-16-87	BOR-10-87	13	65	66.5	139.5	138			GP									29			4.3803	12.94	88.3	9.9	1.6							

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
205	09-16-87	BOR-10-87	14	70	71.5	134.5	133	73.5		GP									49			7.0307	22.80	95 2	4 2	0.5							
206	09-16-87	BOR-10-87	15	75	78.5	129.5	127	78.0		GW									46			1.2289	8.17	74.1	24 8	1.1							
207	09-16-87	BOR-10-87	16	80	81.5	124.5	123	83 0		CL			24	40	14	26			43														
208	09-16-87	BOR-10-87	17	85	86.5	118.5	117	88.5		CH			26						38														
209	09-16-87	BOR-10-87	18	90	91.5	104.5	103	93.5		CL			23	44	14	30			59														
210	09-16-87	BOR-10-87	19	95	96.5	98 5	97	98.0		CH			20						61														
211	09-16-87	BOR-10-87	20	102	103 5	94.5	93	103.5		CH			21						32														

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14. ABSTRACT
The need exists for development of in situ techniques for more accurately determining site conditions offshore of dams and levees in lakes and reservoirs within hazard areas. This report describes the use of a new data processing approach utilizing a Biot theory approach to assess acoustic sediment interactions in porous, saturated media. Ramifications of the Biot theory may aid engineering in accurately assessing liquefaction potential of Corps structures.

15. SUBJECT TERMS
Arkabutla, Biot, Geoacoustic, Geophysics, Reservoir, Seismic, Waterborne

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